The Geometry of Cold, Metal-enriched Gas around Galaxies at z \sim 1.2

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Abstract

We present the first results from a Hubble Space Telescope Wide Field Camera 3/Infrared program, which obtained direct imaging and grim observations of galaxies near quasar sightlines with a high frequency of uncorrelated foreground Mg II absorption. These highly efficient observations targeted 54 Mg II absorbers along the line of sight to nine quasars at z_{\text{qso}} \sim 2. We find that 89% of the absorbers in the range of 0.64 < z < 1.6 can be spectroscopically matched to at least one galaxy with an impact parameter of less than 200 kpc and |Δz|/(1 + z) < 0.006. We have estimated the star formation rates and measured structural parameters for all detected galaxies with impact parameters in the range of 7–200 kpc and star formation rates greater than 1.3 M_\odot yr\textsuperscript{-1}. We find that galaxies associated with Mg II absorption have significantly higher mean star formation rates and marginally higher mean star formation rate surface densities compared to galaxies with no detected Mg II. Nearly half of the Mg II absorbers match more than one galaxy, and the mean equivalent width of the Mg II absorption is found to be greater for groups, compared to isolated galaxies. Additionally, we observe a significant redshift evolution in the physical extent of Mg II-absorbing gas around galaxies and evidence of an enhancement of Mg II within 50° of the minor axis, characteristic of outflows, which persists to 80 kpc around the galaxies, in agreement with recent predictions from simulations.

Unified Astronomy Thesaurus concepts: Quasar absorption line spectroscopy (1317); Galaxy evolution (594); Galaxy winds (626); Circumgalactic medium (1879)

1. Introduction

The in situ evolution of galaxies is understood to be regulated by the accretion, consumption, heating, and expulsion of gas. Distant luminous quasars are uniquely powerful probes of these gaseous processes, as they enable the detection of intervening galaxies by virtue of their gas cross sections, irrespective of their stellar luminosities, from the earliest epochs of galaxy formation to the present.

The most prolific metal absorption transition in optical quasar spectra, singly-ionized magnesium (Mg II), traces T \sim 10^4 K photoionized gas in a wide range of environments in and around intervening galaxies. Absorption from Mg II is expected, in theory, to occur in sightlines probing the interstellar and circumgalactic medium (CGM) of galaxies (e.g., Bahcall & Spitzer 1969; Prochaska & Wolfe 1997), large-scale star formation-driven outflows (e.g., Nulsen et al. 1998), and gas being stripped or accreted within the extended halos of galaxies (e.g., Kacprzak et al. 2010a; Stewart et al. 2011).

Despite the potential utility of Mg II for tracing this wide variety of physical processes that have been implicated in the evolution of galaxies, mapping the distribution and kinematics of Mg II around galaxies has long posed a challenge. Due to the relative faintness of Mg II host galaxies and their close angular proximity to a much brighter background quasar, the luminous counterparts at the redshifts where Mg II is most easily detected at optical wavelengths (z > 0.3) have, until recently, been difficult to properly resolve from the ground.

In the past decade, the expansive spectroscopic quasar sample of the Sloan Digital Sky Survey (SDSS) has facilitated the detection of tens of thousands of Mg II absorbers (e.g., Nestor et al. 2005; Lundgren et al. 2009; Quider et al. 2011; Zhu & Ménard 2013). Large samples have enabled statistical analyses, which circumvented many difficulties of directly detecting Mg II hosts. Spatial clustering (e.g., Bouche et al. 2006; York et al. 2006; Lundgren et al. 2009; Gauthier et al. 2009; Zhu et al. 2014; Pérez-Rafoiu et al. 2015) and stacking techniques (e.g., York et al. 2006; Zibetti et al. 2007; Ménard et al. 2008; Noterdaeme et al. 2010; Ménard et al. 2011; Bordoloi et al. 2011; Ménard & Fukugita 2012) have provided statistical clues to the typical host galaxy properties as a function of Mg II λ\lambda 2796 rest-frame equivalent width (hereafter, W_\text{Mg II}), which together indicate that the strongest absorbers (W_\text{Mg II} > 1 Å) commonly trace dusty, large-scale outflows from star-forming galaxies.

However, these statistical correlations are not unequivocally supported by many observations at low redshift where the host galaxies can more easily be directly observed (e.g., Chen et al. 2010); and despite their statistical links to vigorously star-forming galaxies, many galaxy hosts of high-W, Mg II absorption remain
undetected in even the deepest ground-based observations (Bouché et al. 2007, 2012a), and some ultra-strong absorbers can be explained by the dynamics of gas in an intragroup medium (Gauthier 2013). Studies of directly detected host galaxies at $z < 0.5$ indicate that the origins of Mg II are even less clear in the case of the more common population of absorbers with $W_r < 1$ Å, suggesting that Mg II most frequently probes infalling gas from the halos of normal galaxies (Chen et al. 2010, 2010a; Kacprzak et al. 2011a).

Recent advances in integral field spectroscopy have enabled more efficient searches for the luminous counterparts of quasar absorption systems with considerably higher completeness. Surveys of quasar fields using the Very Large Telescope/Multi Unit Spectroscopic Explorer (VLT/MUSE; Bacon et al. 2010) have revealed that a single absorber can often be matched spectroscopically to multiple galaxies at the same redshift (e.g., Bielby et al. 2017; Péroux et al. 2017; Klitsch et al. 2018; Rahmani et al. 2018; Péroux et al. 2019; Hamanowicz et al. 2020; Bielby et al. 2020; Dutta et al. 2020), suggesting that multiple galaxies may contribute to intragroup gas (Whiting et al. 2006; Kacprzak et al. 2010b; Gauthier 2013) and further complicating the process of correlating galaxy and absorber properties. These findings have called into question a long-standing simplifying assumption that an absorber can be assigned with high confidence to the nearest spectroscopically confirmed galaxy (e.g., Bergeron et al. 1988; Bergeron & Boissé 1991; Steidel et al. 1994; Le Brun et al. 1997). Thus, the historic observational challenge of spectroscopically confirming even one candidate host galaxy for a particular absorber has now been replaced by the new challenge of determining which and how many galaxies with matching redshifts are truly associated with any single absorption system.

These recent advances in ground-based integral field spectroscopy, which have dramatically improved the efficiency in detecting the luminous counterparts of quasar absorbers, still lack the ability to resolve galaxies at small impact parameters (<1.5") to the background quasar. This limitation is particularly problematic for studies of absorption-selected galaxies at high redshift. Space-based observations are thus still required in order to mitigate the possibility of absorber host galaxies being missed as a result of being blended with the point-spread function (PSF) of the brighter quasar.

By analyzing observations of a single quasar from the A-Grism H-Alpha SpecTroscopic survey (AGHAST; Weiner & AGHAST Team 2014) and 3D-Hubble Space Telescope (HST) surveys (van Dokkum et al. 2011; Brammer et al. 2012), Lundgren et al. (2012) provided a proof of concept that relatively shallow HST Wide Field Camera/Infrared (WFC3/IR) G141 grism observations could be used to detect H$\alpha$ emission from the host galaxies of $1 < z < 2$ Mg II absorbers. The three absorber-galaxy pairs identified by Lundgren et al. (2012) had stellar masses consistent with estimates for the strong Mg II absorber population from large-scale clustering analyses (Lundgren et al. 2011). The star formation rate (SFR) surface densities of each galaxy were also estimated and found to exceed the threshold of local galaxies with large-scale outflows. However, due to the small sample size, it was not possible to determine whether there was any particular azimuthal geometry to the Mg II-absorbing CGM, which could provide additional clues to the wind-driving capacity of the $z \sim 1.5$ Mg II host galaxies.

The survey described in this paper utilizes this same observational technique as Lundgren et al. (2012): harnessing the unique capabilities of the WFC3/IR camera and grism onboard the HST to measure the star formation rates (SFRs), impact parameters, inclination angles and structural parameters for 54 Mg II-selected galaxies near the epoch of peak star formation. Our targets are drawn from the largest multi-ion samples of quasar absorption lines compiled to date (D. G. York et al. 2021 in preparation) from SDSS Data Release 7 (Abazajian et al. 2009; Schneider et al. 2010) and SDSS-III Data Release 9 (Ahn et al. 2012; Pâris et al. 2012). By mining these samples we have identified the nine SDSS quasar sightlines richest in $W_r > 0.1$ Å Mg II absorption. Despite the exceptionally high incidence of Mg II in these spectra, the absorbers are all widely separated in redshift and physically uncorrelated; thus, their chance alignment is not expected to bias their physical properties or environments. Using WFC3/IR imaging and grism observations of these fields we have analyzed the properties of a complete magnitude-limited sample of Mg II-selected galaxies at $z > 0.7$, where fewer than 100 Mg II host galaxies have been spectroscopically confirmed to date.

The observations contributing to this work are described in Section 2, and details of our analysis are given in Section 3. In Section 4, we present a discussion of the results and their implications with regard to the evolving distribution of Mg II around galaxies from $z \sim 2$. Throughout this paper, we assume a flat $\Lambda$-dominated cold dark matter cosmology with $\Omega_m = 0.3$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and $\sigma_8 = 0.8$ unless otherwise stated.

2. Observations

2.1. Quasar Observations in the SDSS

The quasar observations used in this analysis are drawn from SDSS DR7 (Abazajian et al. 2009; Schneider et al. 2010) and SDSS-III DR9 (Ahn et al. 2012; Pâris et al. 2012). Each of the quasar spectra was run through an automated pipeline that detects strong ($W_r > 0.1$ Å) Mg II absorption systems. A detailed description of this process is provided in Lundgren et al. (2009). In brief, this pipeline extracts all $\geq 3\sigma$ absorption features in continuum-normalized quasar spectra. The flux of each line is fit with a Gaussian profile to extract precise centroid and equivalent width measurements. In order to identify the ion and redshift corresponding to each measured absorption line, a line matching algorithm identifies pairs of $4\sigma$ absorber detections with the correct wavelength separation expected for the doublet transitions of Mg II ($\lambda\lambda$ 2796, 2803 Å) at a given redshift. The reliability of the identification is further quantified for each detected absorption system, taking into account the doublet ratio measured for Mg II, the number of additional ions matched in absorption at the same redshift, and any blending with other absorption features identified at another redshift.

From the catalogs extracted using this automated pipeline, we then identified all high signal-to-noise ratio (S/N > 15) quasar spectra with five or more physically uncorrelated and unambiguously intervening (v/c > 0.05 in the quasar rest frame) Mg II systems at $z > 0.64$, where H$\alpha$ emission is accessible with the G141 grism. All spectra meeting these criteria were then visually inspected to ensure the validity of the identified absorbers and the absence of additional complicating features such as broad absorption lines. The sample of candidate quasars was then
quasar surveys. Figure 3 illustrates the Hα flux limit for galaxies detected in this work, compared to other studies of Mg II-absorbing galaxies at similar redshifts.

### 2.2. HST WFC3/IR Observations

Following a similar strategy to that of the AGHAST Survey (Weiner & AGHAST Team 2014), the 600 arcmin$^2$ 3D-HST Survey (van Dokkum et al. 2011; Brammer et al. 2012) employed HST/WFC3 G141 grism observations, paired with HST/WFC3 F140W direct imaging, to extract two-dimensional spectra for $\sim$80,000 objects to a $5\sigma$ limiting depth of $m_{1700} \sim 26$ and produce a galaxy redshift catalog comparable to the deepest ground-based surveys (Momcheva et al. 2016). As shown in Lundgren et al. (2012), which leveraged the observations and data products from AGHAST and 3D-HST WFC3/IR grism observations also enable the efficient detection and redshift confirmation of galaxies at $1 < z < 2$ with small impact parameters ($\gtrsim 7$ kpc) to quasars. Our program has adopted this well-tested approach in order to build up a relatively large sample of high-redshift galaxy-absorber pairs, with the aim of better understanding the properties of absorption-selected galaxies at these redshifts.

In an 18-orbit Cycle 21 HST general observing program (GO-13482, PI: Lundgren) we obtained four dithered G141 grism exposures for each quasar target along with a short (4 × 200 s) direct image in F140W, which is necessary for target identification, wavelength, and flux calibration, and for characterizing the structural parameters of the absorber host galaxies. Each two-orbit visit consisted of a guide star acquisition and reacquisition and four pairs of dithered (with half pixel offsets) 200 s F140W images and 1150 s G141 grism exposures.

Given our selection of quasars with a high incidence of intervening absorption, we anticipated that contamination from many galaxies in close proximity to the quasar on the sky could be a complicating factor. Thus, we applied a random position angle offset between each of the two G141 visits, in order to minimize the potential effects of contamination from the overlapping spectra of closely spaced galaxies. These orientation offsets enabled us to combine the full G141 data for the maximum S/N for clearly observed galaxy grism spectra, and to extract spectral information from individual orientations for galaxies that were catastrophically contaminated by another bright nearby object in an individual orientation.

We obtained F140W direct imaging and G141 spectra for galaxies in the targeted fields to a limiting magnitude of $m_{1400W} = 24$ and a limiting $3\sigma$ Hα flux limit of $3 \times 10^{17}$ erg s$^{-1}$ cm$^{-2}$ (equivalent to an SFR $> 1.3 \ M_\odot$ yr$^{-1}$ at $z = 1$, assuming a Salpeter initial mass function) and at impact.

### Table 1

Quasar Targets

| Field | Name | R.A. J2000 | Decl. J2000 | zspec | SDSS Plate | SDSS Fiber | SDSS MJD | Mg II Absorbers |
|-------|------|------------|-------------|-------|------------|------------|---------|-----------------|
| 0     | SDSS J001453.19 + 091217.6 | 3.7216917 | 9.20492 | 2.338 | 4536 | 770 | 55,857 | 9 |
| 1     | SDSS J082946.90 + 185222.0 | 12.474509 | 18.87293 | 1.792 | 2275 | 279 | 53,709 | 5 |
| 2     | SDSS J083852.05 + 025703.7 | 129.71690 | 2.95101 | 1.771 | 3809 | 414 | 55,533 | 7 |
| 3     | SDSS J091730.18 + 324105.5 | 130.37575 | 32.68463 | 2.017 | 1592 | 187 | 52,990 | 9 |
| 4     | SDSS J095432.63 + 354027.7 | 148.63599 | 35.67459 | 2.715 | 4573 | 140 | 55,587 | 7 |
| 5     | SDSS J110742.74 + 102126.3 | 166.92809 | 3.30731 | 1.925 | 5361 | 900 | 55,973 | 6 |
| 6     | SDSS J113233.63 + 380346.4 | 173.14014 | 38.06290 | 2.302 | 4648 | 340 | 55,673 | 5 |
| 7     | SDSS J120342.24 + 102831.8 | 180.92601 | 10.47548 | 1.888 | 1228 | 556 | 52,728 | 5 |
| 8     | SDSS J120639.85 + 025308.3 | 181.66607 | 2.88564 | 2.518 | 4748 | 726 | 55,631 | 6 |

Further reduced by removing objects close to bright nearby stars, which would saturate the HST observations. We also required that the quasars be fainter than $m_i = 17$ to facilitate the detection of galaxies in close angular proximity to the background quasar.

Our final sample is composed of the nine quasars listed in Table 1. The selected quasar spectra exhibit a total of 44 high-confidence Mg II absorbers in the redshift range accessible by Hα in G141 (0.64 $< z \leq 1.6$), spanning an equivalent width range of $0.2 < W_e < 2.5$ Å. These spectra additionally include 12 absorption systems at $1.6 < z < 2.5$, whose host galaxies could also be determined by the detection of O[III]/Hβ emission in the G141 grism observations.

The catalog of absorption systems targeted by this program is presented in Table 2, which includes redshifts and observed-frame equivalent width measurements for all identified Mg II doublets. Absorption systems that report a measurement for only the $\lambda$2796 Å Mg II transition indicate cases where corresponding absorption at the wavelength of the weaker $\lambda$2803 Å transition fell below our $3\sigma$ detection threshold. Some of the higher redshift absorption systems listed in Table 1 lack equivalent width measurements for both transitions of Mg II; these are cases in which an absorption system was detected by the presence of a C IV ($\lambda$1548, 1550 Å) doublet, and either the Mg II doublet was inaccessible due to the wavelength limitations of the SDSS spectrum, or both lines were undetected at the $3\sigma$ level. Such systems were not included in our galaxy-absorber pair analysis but are documented for completeness. Any detected absorption systems that have low confidence due to line blending, multiple degenerate line identifications, or having too few matching lines to provide an unambiguous redshift identification are flagged in the table and have been excluded from further analysis. Additionally, galaxies with poorly determined morphologies did not produce reliable azimuthal angles, and we did not attempt to find the morphologies of galaxies with uncertain grism redshifts.

A typical quasar spectrum from our sample is shown in Figure 1. The SDSS quasar spectra for sightlines targeted in this survey have a spectral resolution ($R \sim 1800$) and mean S/N comparable to that of the Keck Deep Imaging Multi-object Spectrograph spectrum from our pilot study (Lundgren et al. 2012). In Figure 2, we compare the rest-frame equivalent width ($W_e$) and redshift distribution of the Mg II absorbers in our sample to that of other surveys of Mg II host galaxies at similar sensitivities. The global distribution of the $\sim$30,000 Mg II absorbers detected in the SDSS DR7 quasar catalog of D. G. York et al. (2021 in preparation) is shown in contours, demonstrating that our targets sample a larger dynamic range in $W_e$ and also more accurately represent the global population of Mg II absorbers detected in medium resolution spectroscopic...
| Target | \(z_{\text{obs}}\) | \(W_{\text{OII}}^{269}\) (Å) | \(W_{\text{OIII}}^{295}\) (Å) | Flag\(^{a}\) | \(z_{\text{gal}}\) | \(\rho\) (kpc) | \(\phi\) (deg) | \(F_{\text{abs}}\) \((10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2})\) | Flag\(^{b}\) | Flag\(^{c}\) |
|--------|-----------------|-----------------|-----------------|--------|-----------------|-----------------|-----------------|-----------------|-----------------|--------|--------|
| 0      | 0.66759         | 1.426 ± 0.072   | 1.952 ± 0.112   | 0      | 0.673           | 67.7            | 18.7            | 36.5 ± 7.2      | 0     | 1      |
| 1      | 1.14918         | 1.348 ± 0.106   | 1.208 ± 0.116   | 0      | 1.145           | 74.2            | 33.9            | 9.6 ± 3.5       | 0     | 1      |
| 1      | 1.17525         | 2.249 ± 0.11    | 1.796 ± 0.107   | 0      | 1.160           | 121.1           | ...             | 0.6 ± 1.2       | 0     | 0      |
| 1      | 1.22071         | 2.998 ± 0.11    | 2.172 ± 0.102   | 0      | 1.236           | 56.5            | ...             | 1.0 ± 3.2       | 0     | 1      |
| 1      | 1.52965         | 2.269 ± 0.117   | 1.449 ± 0.112   | 0      | 1.524           | 99.8            | 70.4            | 4.7 ± 1.4       | 0     | 1      |
| 1      | 1.56403         | 2.620 ± 0.099   | ...             | 0      | 1.574           | 38.0            | 43.8            | 12.8 ± 11.4     | 0     | 1      |
| 1      | 1.56916         | 6.873 ± 0.137   | 3.631 ± 0.126   | 0      | 1.574           | 38.0            | 43.8            | 12.8 ± 11.4     | 0     | 1      |
| 2      | 1.23426         | 0.898 ± 0.173   | ...             | 0      | ...             | ...             | ...             | ...             | ...             | ...   |
| 2      | 1.22914         | 0.737 ± 0.083   | ...             | 0      | ...             | ...             | ...             | ...             | ...             | ...   |
| 1      | 0.85303         | 1.005 ± 0.091   | 1.151 ± 0.129   | 0      | 0.844           | 63.9            | 49.1            | 5.4 ± 3.0       | 0     | 1      |
| 1      | 1.01773         | 1.945 ± 0.183   | 0.969 ± 0.14    | 0      | ...             | ...             | ...             | ...             | ...             | ...   |
| 1      | 1.36680         | 2.732 ± 0.144   | 2.574 ± 0.149   | 0      | 1.361           | 65.0            | 56.5            | 29.9 ± 2.2      | 0     | 1      |
| 1      | 1.40842         | 1.224 ± 0.102   | 1.073 ± 0.101   | 0      | 1.407           | 84.5            | 54.1            | 0.0 ± 0.1       | 0     | 1      |
| 1      | 1.80016         | 4.243 ± 0.177   | 3.628 ± 0.184   | 0      | ...             | ...             | ...             | ...             | ...             | ...   |
| 2      | 0.82426         | 0.476 ± 0.058   | 0.162 ± 0.036   | 0      | 0.821           | 137.8           | 42.7            | 16.6 ± 3.0      | 0     | 1      |
| 2      | 0.94003         | 1.474 ± 0.070   | ...             | 0      | 0.934           | 102.7           | ...             | 3.6 ± 1.7       | 0     | 1      |
| 2      | 1.09951         | 0.194 ± 0.035   | ...             | 0      | 1.095           | 60.6            | ...             | 22.0 ± 2.7      | 0     | 1      |
| 2      | 1.33095         | 3.624 ± 0.067   | 2.787 ± 0.074   | 0      | 1.325           | 40.0            | 51.9            | 0.9 ± 2.0       | 0     | 1      |
| 2      | 1.41576         | 2.240 ± 0.067   | 1.448 ± 0.071   | 0      | 1.395           | 93.2            | ...             | 15.0 ± 1.5      | 0     | 0      |
| 2      | 1.44630         | 2.182 ± 0.072   | 1.965 ± 0.07    | 0      | 1.448           | 87.8            | ...             | 12.0 ± 1.5      | 0     | 1      |
| 2      | 1.66407         | 2.074 ± 0.086   | 1.334 ± 0.089   | 0      | ...             | ...             | ...             | ...             | ...             | ...   |
| 3      | 1.22947         | 2.542 ± 0.202   | 2.536 ± 0.164   | 0      | 1.225           | 39.6            | 69.2            | 8.1 ± 1.9       | 0     | 1      |
| 3      | 1.41294         | 4.538 ± 0.176   | 4.253 ± 0.186   | 0      | 1.415           | 15.7            | 51.8            | 13.9 ± 4.5      | 0     | 1      |
| 3      | 1.45627         | 2.043 ± 0.338   | ...             | 1      | ...             | ...             | ...             | ...             | ...             | ...   |
| 3      | 1.53688         | ...             | ...             | 0      | ...             | ...             | ...             | ...             | ...             | ...   |
| 4      | 1.07438         | 4.109 ± 0.188   | 3.36 ± 0.204    | 0      | 1.072           | 19.3            | ...             | 6.2 ± 3.0       | 0     | 1      |
| 4      | 1.18256         | 5.857 ± 0.276   | 5.128 ± 0.268   | 0      | 1.188           | 120.1           | 4.1             | 2.0 ± 1.9       | 0     | 1      |
| 4      | 1.35044         | 0.727 ± 0.111   | 0.756 ± 0.201   | 0      | ...             | ...             | ...             | ...             | ...             | ...   |
| 4      | 1.44949         | 1.606 ± 0.182   | 1.219 ± 0.211   | 0      | 1.442           | 63.9            | 44.5            | 9.7 ± 1.1       | 0     | 1      |
| 4      | 1.70888         | 1.758 ± 0.222   | 1.728 ± 0.217   | 0      | ...             | ...             | ...             | ...             | ...             | ...   |
Table 2 (Continued)

| Target | z_{obs} | W_{obs}^{796} (Å) | W_{obs}^{2051} (Å) | Flag^a | z_{gal} | \rho (kpc) | \phi (deg) | \phi_{Bol} (10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}) | Flag^b | Flag^c |
|--------|---------|-------------------|-------------------|---------|---------|-----------|-----------|---------------------------------|---------|---------|
| 1.73440 | 1.614 \pm 0.199 | 1.457 \pm 0.187 | 0 | ... | ... | ... | ... | ... | ... | ... |
| 2.01760 | ... | ... | 0 | ... | ... | ... | ... | ... | ... | ... |
| 2.10673 | 1.901 \pm 0.281 | 0.778 \pm 0.175 | 0 | ... | ... | ... | ... | ... | ... | ... |
| 5 | 0.74548 | 3.942 \pm 0.056 | 2.888 \pm 0.055 | 0 | 0.741 | 35.4 | ... | 0.0 \pm 0.0 | 0 | 1 |
| | | & 0.735 & 40.0 & ... & 0.1 \pm 1.4 & 1 & 0 |
| | | & 0.742 & 113.3 & ... & 71.2 \pm 17.1 & 0 & 1 |
| | 1.01540 | 4.111 \pm 0.078 | 1.978 \pm 0.049 | 0 | 1.011 | 43.5 | ... | 10.0 \pm 1.9 | 0 | 1 |
| | 1.04852 | 1.010 \pm 0.065 | 0.907 \pm 0.072 | 0 | ... | ... | ... | ... | ... | ... |
| | 1.14783 | 1.815 \pm 0.069 | 1.114 \pm 0.067 | 0 | ... | ... | ... | ... | ... | ... |
| | 1.29529 | 1.176 \pm 0.081 | 0.742 \pm 0.081 | 0 | 1.295 | 21.7 | ... | 0.0 \pm 0.0 | 1 | 0 |
| | | & 1.277 & 56.8 & ... & 8.4 \pm 3.7 & 1 & 0 |
| | | & 1.289 & 58.3 & ... & 18.3 \pm 2.6 & 0 & 1 |
| | | & 1.291 & 74.0 & ... & 15.2 \pm 4.7 & 0 & 1 |
| | 1.32544 | 6.846 \pm 0.067 | 6.114 \pm 0.053 | 0 | 1.325 | 14.7 | ... | 0.0 \pm 0.0 | 1 | 0 |
| | | & 1.336 & 69.7 | ... | 10.1 \pm 1.6 | 0 | 1 |
| | | & 1.340 & 159.0 | ... | 8.6 \pm 1.6 | 0 & 0 |
| | 1.60117 | ... | ... | 0 | ... | ... | ... | ... | ... | ... |
| | 1.71102 | ... | ... | 0 | ... | ... | ... | ... | ... | ... |
| | 1.86376 | ... | ... | 0 | ... | ... | ... | ... | ... | ... |
| | 1.88273 | ... | ... | 0 | ... | ... | ... | ... | ... | ... |
| 6 | 0.92480 | 1.538 \pm 0.084 | 1.265 \pm 0.086 | 0 | 0.919 | 40.8 | 54.9 | 5.8 \pm 1.8 | 0 & 1 |
| | | & 0.922 & 142.9 & 0.0 & 16.4 \pm 2.4 & 0 & 1 |
| | | & 0.915 & 176.8 | 82.9 | 6.7 \pm 3.0 & 0 & 0 |
| | 1.15147 | 0.919 \pm 0.119 | 0.604 \pm 0.108 | 0 | ... | ... | ... | ... | ... | ... |
| | 1.19213 | 2.027 \pm 0.106 | 1.873 \pm 0.107 | 0 | ... | ... | ... | ... | ... | ... |
| | 1.27638 | 2.197 \pm 0.113 | 2.152 \pm 0.112 | 0 | 1.275 | 86.2 | 70.2 | 46.6 \pm 2.0 | 0 & 1 |
| | | & 1.281 & 158.5 | ... | 1.5 \pm 8.7 | 1 & 0 |
| | | & 1.274 & 171.0 | 49.1 | 20.6 \pm 2.1 | 0 & 0 |
| | 1.38301 | 0.930 \pm 0.109 | 0.633 \pm 0.124 | 0 | 1.389 | 55.7 | 71.2 | 1.2 \pm 5.5 | 0 & 1 |
| | 1.75775 | ... | ... | 1 | ... | ... | ... | ... | ... | ... |
| | 2.07231 | ... | ... | 0 | ... | ... | ... | ... | ... | ... |
| | 2.82482 | ... | ... | 0 | ... | ... | ... | ... | ... | ... |
| 7 | 0.73955 | 1.286 \pm 0.115 | 0.878 \pm 0.116 | 0 | 0.740 | 39.1 | 12.4 | 0.0 \pm 0.0 | 0 & 1 |
| | | & 0.745 & 71.5 | 69.0 | 1.5 \pm 14.6 | 1 & 0 |
| | 0.74595 | 4.719 \pm 0.137 | 3.935 \pm 0.132 | 0 | 0.740 | 39.1 | 12.4 | 0.0 \pm 0.0 | 0 & 0 |
| | | & 0.745 & 71.5 | 69.0 | 1.5 \pm 14.6 | 1 & 0 |
| | 1.32224 | 0.998 \pm 0.129 | 0.611 \pm 0.102 | 0 | 1.334 | 92.3 | 55.4 | 5.4 \pm 1.0 | 0 & 1 |
| | | & 1.339 & 95.7 | 35.7 | 1.7 \pm 3.1 | 0 & 0 |
| | 1.34230 | 1.668 \pm 0.125 | 1.234 \pm 0.128 | 0 | 1.334 | 92.3 | 55.4 | 5.0 \pm 2.1 | 0 & 0 |
| | | & 1.339 & 95.7 | 35.7 | 1.7 \pm 3.1 | 0 & 0 |
| | 1.57449 | ... | ... | 1 | ... | ... | ... | ... | ... | ... |
| | 1.57876 | 1.796 \pm 0.126 | 1.472 \pm 0.137 | 0 | 1.566 | 40.4 | 83.8 | 9.5 \pm 5.3 | 0 & 1 |
| | | & 1.589 & 56.2 | ... | 19.1 \pm 28.4 | 1 & 0 |
| | 1.79606 | ... | ... | 0 | ... | ... | ... | ... | ... | ... |
| 8 | 0.68079 | 1.309 \pm 0.084 | 0.477 \pm 0.069 | 1 | 0.675 | 33.4 | ... | 29.9 \pm 5.0 | 0 & 0 |
| | | & 0.691 | 118.4 | ... | 12.1 \pm 3.4 | 0 & 0 |
| | | & 0.686 | 131.2 | ... | 1.9 \pm 4.2 | 1 & 0 |
| | 0.82150 | 1.902 \pm 0.109 | 1.386 \pm 0.102 | 0 | 0.815 | 65.0 | 66.5 | 9.9 \pm 2.7 | 0 & 1 |
| | | & 0.819 | 85.7 | 25.6 | 8.2 \pm 3.4 | 0 & 1 |
| | | & 0.812 | 99.7 | 71.6 | 0.2 \pm 0.8 | 0 & 1 |
| | | & 0.817 | 116.4 | 18.1 | 50.5 \pm 3.8 | 0 & 1 |
| | 0.94898 | 0.814 \pm 0.075 | 0.408 \pm 0.067 | 0 | 0.956 | 36.9 | 65.2 | 8.9 \pm 2.2 | 0 & 1 |
| | | & 0.946 | 76.6 | 9.4 | 3.6 \pm 0.7 | 0 & 1 |
| | 0.96149 | 0.809 \pm 0.078 | 0.45 \pm 0.086 | 0 | 0.956 | 37.0 | 65.2 | 8.9 \pm 2.2 | 0 & 0 |
parameters around the central quasar limited only by the quasar PSF ($\lesssim 5$ kpc) and the field of view ($\lesssim 480$ kpc at $z = 1$). The G141 grism observations provided slitless spectroscopy over the wavelength range of 1.10–1.65 μm with a first-order dispersion of 46.5 Å pixel$^{-1}$ ($R \sim 130$) and a spatial resolution of $\sim 0.13''$, sampled with 0.06'' pixels. These specifications enabled the detection of Hα emission in the redshift range of $0.64 < z < 1.6$, [OIII]λ5007 in the range of $1.2 < z < 2.3$, and [OII]λ3727 for $2.0 < z < 3.4$.

### 3. Analysis

#### 3.1. Analysis of Foreground Galaxies

The WFC3/IR galaxy observations were reduced and analyzed using a variation on the method described in Brammer et al. (2012). This process relies on first detecting sources in the F140W images using SExtractor (Bertin & Arnouts 1996) and then extracting the individual G141 spectra for each source, minus the modeled contamination from the sky background and any nearby
either Hα limitations correspond to the range in which emission from Hβ is observable in the G141 grism data. The highest confidence galaxy redshifts are determined from G141 spectra with multiple strong emission lines. Galaxies without emission lines (e.g., quiescent galaxies) generally did not allow for conclusive redshift determinations unless the continuum S/N was high.

Based on the findings of Brammer et al. (2012) and Momcheva et al. (2016), we estimate the galaxy redshifts in this work have a typical precision of |Δz|/(1 + z) = 0.0035 at z > 0.7. However, the precision is expected to increase with the strength and number of emission lines in each G141 spectrum. Bielby et al. (2019), which compared spectroscopic redshifts of galaxies with 3 hr VLT/MUSE observations and eight orbits of coverage with HST/WFC3 G141, reported that the R = 130 spectral resolution of the G141 grism results in a typical velocity accuracy of σz = 682 km s⁻¹ at z = 1.

For each of the galaxies with Hα emission line measurements in the G141 spectra we estimate the SFR using the relation from Kennicutt (1998):

$$\text{SFR}_{H\alpha} [M_\odot \text{yr}^{-1}] = \frac{L_{H\alpha}}{7.9 \times 10^{-42} \text[erg s}^{-1}] \cdot (1)$$

which assumes the initial mass function of Salpeter (1955). Given the wavelength range of the grism data, the Hα and Hβ emission lines are not concurrently accessible for the galaxies with z < 1.2. Subsequently, we have not been able to apply a standard correction for dust extinction to the Hα flux measurements in our full sample, and these estimated SFRs represent lower limits. We also note that at the resolution of the WFC3/IR G141 grism spectroscopy, Hα, and NII emission are unresolved. Thus, we expect that the Hα fluxes are also overestimated on the order of 25%–33% (Villar et al. 2008; Geach et al. 2008; Sobral et al. 2009).

For galaxies in which emission lines are not evident or observable in the G141 1D spectra, ancillary multiband photometric observations are required to precisely estimate the stellar masses and SFRs with stellar population synthesis modeling. Future follow-up multiwavelength HST imaging of these fields would add significant value to this survey and will be pursued in upcoming cycles.

### 3.1.1. Matching Galaxies to MgII Absorption

In searching for galaxies matching the MgII absorbers in our targeted quasars, we have limited our analysis to the redshift range in which Hα is observable in the G141 grism data (0.64 ≤ z ≤ 1.6). These limits provide a homogeneous sample for which the SFRs can be determined in a self-similar way. We also include in our search only galaxies with apparent magnitudes of m_{140} < 25 and high-confidence redshifts, as determined through careful visual inspection of the extracted grism spectrum for each galaxy. We required that the galaxies match in redshift to MgII within |Δz|/(1 + z_{MgII}) < 0.006,
equivalent to $\Delta v < 900$ km s$^{-1}$ at $z = 1$, and have an impact parameter of less than 200 kpc. The redshifts of the quasar absorption line systems have been precisely determined to five decimal places by taking the average redshift of the individually modeled centroids for each $3\sigma$ absorption line identified in each system. Thus, the uncertainty in matching galaxies to the MgII systems lies exclusively in the galaxy redshift estimation from the grism data. Resolved galaxies matching the aforementioned criteria whose redshifts were determined to be unreliable during the process of visual inspection have been flagged in the second-to-last column of Table 2.

As a demonstration of our data quality, the annotated F140W direct image for one of the nine fields (Field 2; SDSS J083842.05+025703.7) is shown in Figure 4, alongside the 2D and 1D G141 grism spectra of the galaxies with impact parameters less than 200 kpc and well-determined redshifts matching to a detected MgII absorption system.

3.1.2. Notes on Individual Fields

Foreground galaxies with small ($<7$ kpc) impact parameters are often difficult to resolve from the quasar PSF, and the orientation of the grism spectra can lead to catastrophic contamination that makes the galaxy redshifts impossible to determine. This means that, for some fields, information about our census of foreground galaxies may be incomplete. As shown in Figure 5, Field 5 is problematically crowded, with three galaxies detected within $4''$ of the background quasar. While each of these galaxies is clearly resolved in the imaging, galaxy D was not separately resolved from galaxy C in the grism data. Additionally, galaxies B and C each suffered catastrophic contamination from the quasar and another nearby galaxy in both of the randomly chosen orientations for the grism observations. Our inability to extract redshifts for these three galaxies introduced an unacceptable level of uncertainty into our galaxy-absorber matching for this field. Thus, we ultimately excluded it from our full analysis.

For comparison in Figure 5 we show that in the case of Field 3, which has no crowding, the spectrum for a galaxy with a similarly small impact parameter ($\rho = 16$ kpc) could be successfully extracted despite one of the grism orientations being heavily contaminated by the quasar. Fitting the grism data for galaxy A, using the second orientation angle alone, produced a spectrum with a cleanly detected H\textalpha emission line, leading to a well-determined redshift of $z = 1.415$, which matches a MgII absorber at $z_{\text{abs}} = 1.413$. Taken together, Fields 3 and 5 demonstrate the benefit of multiple grism orientations for obtaining galaxy spectra at small impact parameters to a background quasar and also the limitations of this observational method in crowded fields.

In order to determine whether resolvable galaxies are present at even smaller impact parameters, we used the robust 2D galaxy modeling software package Galfit (Peng et al. 2010) to fit and...
subtract the empirically determined PSF in each field from the central quasar image. In Figure 6, we present image cutouts of the central quasar from each field with pixels associated with resolved galaxies masked. Beside each cutout is the residual image that resulted from subtracting a scaled PSF from the quasar profile. The residual images in Fields 1, 4, 7, and 8 revealed possible unresolved galaxies with small angular separations from quasars SDSS J082946.90 + 185222.0, SDSS J095432.63 + 354027.7, SDSS J120342.24 + 102831.8, and SDSS J120639.85 + 025308.3, respectively. As we were unable to extract grism spectra for these sources, their redshifts are undetermined. Consequently, these sources are not accounted for in our analysis.

The quasar PSF subtraction for Field 7 reveals two faint sources within 3″ of the quasar, whose small sizes may suggest a high-redshift origin. Either of these could match the absorption system at $z = 1.79606$ observed in the spectrum of SDSS J120342.24 + 102831.8. This absorber was detected due to the presence of CIV absorption and other lines with similarly high ionization, but it was not included in our analysis due to the apparent absence of associated MgII absorption. We discuss the overall completeness of the galaxy-quasar pair sample in more detail in Section 4.1.

The PSF-subtracted quasar image in Field 1 (SDSS J082946.90 + 185222.0) also reveals a compact luminous component in the residual. This could correspond to the $W_r = 0.97 \, \text{Å}$ MgII absorber at $z = 1.01773$, which is not matched to any other galaxies in our sample, or the $W_r = 1.52 \, \text{Å}$ absorber at $z = 1.80016$, the latter of which we ignore due to its redshift being outside of the range used in our analysis. Similarly, the apparent residual component in

**Figure 5.** A $10'' \times 10''$ cutout of the F140W direct image from Fields 3 and 5, centered on the quasar in each field. Shown below are the G141 grism spectra for three of the four galaxies labeled in the images. Galaxies C and D were not separately resolved in the reduced grism data, so the spectrum for galaxy C includes the combined emission from both objects. From left to right we present the 2D raw G141 flux, the modeled G141 contamination from nearby sources, and the contamination-subtracted flux for each of the two orientations and the combined stack. The final column presents the best-fit 1D spectrum for each object with the black trace indicating the observed flux and the red trace indicating the best-fit model spectrum. While galaxy A suffers substantial contamination in one orientation, a clean spectrum and reliable redshift determination has been extracted using the second orientation alone. For contrast, galaxies B and C in Field 5 are clearly resolved in the imaging, but their redshifts cannot be determined due to residual contamination in both orientations of the extracted grism spectra.
Field 4 could correspond to the $W_r = 0.31$ Å absorber at $z = 1.35044$, which remains unmatched to any of the galaxies in our sample. Two other absorbers ($W_r = 0.43$ Å at $z = 1.15147$ and $W_r = 0.92$ Å at $z = 1.19213$) that are not matched to any galaxies are found in Field 6, which has a very flat residual in the PSF-subtracted quasar image and no evidence of excess flux. We can state with high confidence that these two absorption systems are not the result of luminous galaxies at very small impact parameters.

3.1.3. Galaxy Morphology

The azimuthal angle ($\phi$) of gas relative to the minor axis of a galaxy (see Figure 7) can be used to infer associations with inflows or outflows around galaxies. To precisely measure the azimuthal distribution of the MgII absorbers around galaxies in our sample requires reliable measurements of the 2D morphologies and orientations of galaxies in the foreground field of each quasar. The high resolution and small native pixel scale (0.06″ pixel$^{-1}$) of the WFC3 F140W images enable us to examine the morphologies of the galaxies proximate to the quasar sightline. Using Galfit, we have derived the effective radius ($R_e$), Sérsic index, axis ratio ($b/a$), and position angle for the galaxies within a projected distance of 200 kpc around each quasar. As input to Galfit, we produced an empirical PSF for each field by stacking the normalized profiles of multiple unsaturated stars. Most fields had several unsaturated stars, and all fields had at least one. Before fitting, each galaxy image was masked to ignore pixels from neighboring galaxies or stars. The masks were generated using the segmentation maps of each field, which were produced using SExtractor (Bertin & Arnouts 1996).

We fit the galaxies with a Sérsic profile, with initial parameters for each of the following: integrated magnitude (obtained from SExtractor), effective radius, Sérsic index, axis ratio, and position angle. For cases in which SExtractor identified two closely spaced or merging galaxies to be separate sources, we modeled each source individually. In order to obtain a satisfactory fit, some galaxies required a two-component (bulge plus disk) model. In such cases, only the disk component was used to determine the position angle. After Galfit converged to the best-fit estimates for these parameters, the model-subtracted residual images were visually inspected to validate the results. If the Galfit modeling diverged or produced catastrophic residuals for all reasonable initial parameters, the morphological measurements were not included in our analysis. We used the best-fit position angle and the image coordinates of the galaxy and the central quasar (obtained from SExtractor) to calculate the azimuthal angle with respect to the quasar.

4. Results

4.1. Sample Completeness

Eight of the nine fields targeted in this survey were determined to be viable for the analysis of absorber-galaxy...
correlations. As we discuss in Section 3.1.2, the one excluded Figure 8. Absorber rest-frame equivalent width (W_r) distribution for 2796 Å Mg II absorbers with and without at least one spectroscopically confirmed galaxy counterpart. This figure includes only absorbers in the redshift range where Hα emission is detectable in the G141 grism data (0.64 < z < 1.6) and excludes absorbers in Field 5.

correlation affects our sample with z < 0.4. Figure 9, we have overplotted log-linear graphs of the form log(W_r) = a*ρ + b applied by Nielsen et al. (2013) to a large sample with z ∼ 0.4 (where a = −0.015 ± 0.002 and b = 0.27 ± 0.11). Fitting the same form to a combined sample of z > 1 pairs from this work, together with the previous works.

described in detail in the next section, one might expect galaxies at small impact parameters to produce absorption systems with high equivalent widths (e.g., Bouché et al. 2012a). However, as shown in Figure 8, the equivalent width distribution of the four absorbers that lack a spectroscopically confirmed galaxy match in our sample is not skewed toward high equivalent widths. This result suggests that the galaxies blended with the quasar PSF are not the missing hosts of the four absorbers lacking galaxy matches. However, we also cannot rule out the possibility that some of higher equivalent width Mg II absorbers in our sample that have spectroscopically confirmed galaxy matches may also match one or more of these galaxies at very small impact parameters, whose redshifts remain undetermined.

4.2. W_r2796 – Impact Parameter Relation

Samples of spectroscopically confirmed galaxy-absorber pairs have gradually grown over the past few decades, revealing a new well-established anticorrelation between galaxy impact parameter and the associated equivalent width of Mg II (e.g., Lanzetta & Bowen 1990; Bergeron & Boissé 1991; Bouché et al. 2006; Kacprzak et al. 2008; Chen et al. 2010; Churchill et al. 2013). This relation has been suggested to explain the strong observed correlation between Mg II equivalent width and dust extinction in background quasars (Ménard et al. 2008), as well as the strong correlation between Mg II equivalent width and [O II] emission observed in stacks of SDSS absorption spectra (Ménard et al. 2011). In Figure 9, we plot the Mg II absorber rest-frame equivalent width versus galaxy impact parameter for high-confidence absorber-galaxy pairs. We find agreement with previous results that indicate an inverse correlation with ∼1 dex of scatter.
of Bouché et al. (2012a), Lundgren et al. (2012), and Schroetter et al. (2019), gives best-fit coefficients of $a = -0.008 \pm 0.001$ and $b = 0.51 \pm 0.03$. The overlaid results, shown in Figure 9, suggest a significant evolution in the relation from $z \sim 1.5$ to $z \sim 0.4$, consistent with circumgalactic Mg II gas extending to larger physical radii around galaxies at earlier times. This could potentially be explained by galaxy-scale winds extending to greater distances at an epoch when galaxies typically had lower masses and higher SFRs. Our findings appear to agree with Lan (2020), who recently reported evolution in the covering fraction of strong Mg II absorption around star-forming galaxies in this same redshift range. However, we caution that the inhomogeneous selection of targets in the included data sets in Figure 9 could also potentially complicate the redshift evolution implied by this comparison.

In a recent study of 27 Mg II absorbers detected around 228 galaxies at $0.8 < z < 1.5$, Dutta et al. (2020) reported an absence of evolution in the $W_r - \rho$ relation compared to literature measurements at $z \sim 0.5$. This discrepancy with our finding could potentially be explained by the fact that the Dutta et al. (2020) sample was selected blind to the incidence of Mg II in the spectra of the targeted quasars. In contrast, our $z \sim 1.2$ sample combines surveys of absorption-selected galaxies, which could be biased to tracing outflows and not represent the isotropic average of the radial profile of Mg II around an unbiased sample of galaxies. It is also important to note that the lower redshift ($z \sim 0.5$) measurements from Nielsen et al. (2013), to which both we and Dutta et al. (2020) have compared our higher redshift measurements of the $W_r - \rho$ relation, were obtained through a heterogeneous selection that also includes Mg II-selected quasar fields.

With the possible exception of galaxies with very low cold gas covering fractions (e.g., luminous red galaxies; Bowen & Chelouche 2011, but see also Zhu et al. 2014; Pérez-Ràfols et al. 2015), this anticorrelation appears to hold for a diverse range of galaxy types and can be physically interpreted, to order, as a decreasing covering fraction of low-ionization metal-enriched gas with increasing distance from an average galaxy. The persistent and significant scatter observed in the $W_r - \rho$ relation may be caused by multiple complicating and compounding factors, including: galaxy inclination and azimuthal angle (i.e., the angular position of the detected gas relative to the major axis of the associated galaxy), stellar mass, SFR, and environment.

Bordoloi et al. (2011) and Hamanowicz et al. (2020) observed that the $W_r - \rho$ relation for absorbers matched to multiple galaxies is offset compared to individual galaxies, strengthening the case that environment affects the column density and velocity dispersion of a detected absorption system. Some studies (e.g., Chen et al. 2010a; Kacprzak et al. 2011b; Nielsen et al. 2013) have also reported success at reducing the scatter in this relation by accounting for galaxy luminosity, inclination, and mass. In Section 4.6, we describe a new model for predicting the $W_r$ of a system, by accounting simultaneously for the azimuthal angle, impact parameter, and environment of galaxy-absorber pairs.

### 4.3. Mg II Absorber Environments

Recent IFU studies with improved methods for detecting galaxies in quasar foregrounds have found that it may be common for multiple massive galaxies to be matched to a single absorption system (e.g., Bielby et al. 2017; Péroux et al. 2017; Klitsch et al. 2018; Rahmani et al. 2018; Péroux et al. 2019; Hamanowicz et al. 2020; Bielby et al. 2020). Since our data enable redshift estimates for all galaxies with an SFR $\geq 1M_\odot$ yr$^{-1}$, in each quasar field, we have also been able to investigate the typical environments of Mg II absorbers at $z \sim 1.2$. As shown in Figure 10, nearly half (14/32) of the Mg II absorbers with H$\alpha$ coverage in our survey are spectroscopically matched to more than one galaxy within 200 kpc of the quasar sightline. Furthermore, we find that the Mg II absorption equivalent width ($W_r$) exhibits a weak correlation with environment. The mean Mg II absorption equivalent width for systems matched to apparently isolated galaxies is $0.84 \pm 0.14$ Å, compared to a mean of $1.21 \pm 0.20$ Å for absorbers matched to multiple galaxies.

These findings appear to agree with the recent results of Dutta et al. (2020) and Fossati et al. (2019), whose observations of the MUSE Ultra Deep Field revealed enhanced absorption of Mg II around galaxies in groups, compared to galaxies in more isolated environments. These results suggest that gas stripping from gravitational interactions between galaxies in these dense environments increases the cross section of cool gas and lead to an increased equivalent width in the associated Mg II absorption. Evidence for multiple galaxies contributing to intragroup gas has also been noted by other recent studies (Whiting et al. 2006; Kacprzak et al. 2010b; Gauthier 2013; Johnson et al. 2015).

### 4.4. Mg II Incidence and SFR

An abundance of evidence now supports a correlation between the SFR and the covering fraction of circumgalactic Mg II absorption in galaxies (e.g., Zibetti et al. 2007; Ménard et al. 2008; Noterdaeme et al. 2010; Ménard et al. 2011; Bordoloi et al. 2011; Ménard & Fukugita 2012; Bordoloi et al. 2014b; Lan & Mo 2018). Analyses of the largest samples of Mg II compiled to date have even suggested that evolution of the redshift number density of strong Mg II absorbers can be used to trace the cosmic star formation history from $z \sim 6$ (Matejek & Simcoe 2012; Zhu & Ménard 2013).
While we have provided in Table 2 a full accounting of absorption-matched galaxies detected out to impact parameters of 200 kpc, we will hereafter truncate our analysis at \( \rho < 150 \) kpc in order to minimize the uncertainties introduced by including galaxies with very large physical separations, which are statistically less likely to be truly associated with the detected absorption. In an examination of all galaxies with SFR measurements above our detection threshold and within 150 kpc of the quasar sightline, we find that galaxies associated with Mg II absorption have significantly higher average SFRs compared to galaxies for which no Mg II was detected in the quasar spectrum (see Figure 11). The mean SFR for galaxies with detected Mg II is \( 7.2 \pm 1.3 \)
\( \left[ M_{\odot} \text{yr}^{-1}\right] \), compared to \( 2.9 \pm 0.5 \)
\( \left[ M_{\odot} \text{yr}^{-1}\right] \) for galaxies without a Mg II detection.

In the local universe, galaxy-scale outflows of photoionized \( T \sim 10^4 \) K gas have been observed in association with galaxies with higher than average SFR surface densities (Chisholm et al. 2015; Heckman et al. 2015; Heckman & Borthakur 2016; Ho et al. 2016; Chisholm et al. 2017). These findings support theoretical models in which not only the rate of star formation, but also its physical concentration, determines a galaxy’s capacity for launching large-scale outflows. Supporting this model, a recent analysis by Bordoloi et al. (2014b) reported a strong correlation between the equivalent width of outflowing Mg II gas and the SFR surface density \( \Sigma_{\text{SFR}} \) in 486 zCosmic Evolution Survey (zCOSMOS) galaxies at \( 1 < z < 1.5 \). If a substantial fraction of the Mg II detected in the extended halos of galaxies in our sample originated in star formation-driven winds (rather than, e.g., tidal stripping or infall from the intergalactic medium), we might also expect to observe a correlation between \( \Sigma_{\text{SFR}} \) and the incidence of circumgalactic Mg II absorption.

In order to estimate the \( \Sigma_{\text{SFR}} \) for galaxies in our sample, we produced spatially resolved maps of the H\( \alpha \) emission following the methodology described in Lundgren et al. (2012). However, for most individual galaxies the S/N was too low to precisely measure the morphology of the H\( \alpha \) emitting region. Thus, we have estimated the galaxy sizes using the effective radii extracted from the F140W imaging, which captures the rest-frame stellar continuum emission of the galaxies at the redshift range of our study. We calculate the average SFR surface density, \( \Sigma_{\text{SFR}} \), as

\[
\Sigma_{\text{SFR}}[M_{\odot} \text{yr}^{-1} \text{kpc}^{-2}] = \frac{M_{\odot}}{\pi R_e^2},
\]

where \( M_{\odot} \) is the H\( \alpha \)-derived SFR (Equation (1)) and \( R_e \) is the effective radius enclosing 50% of the flux in the F140W continuum emission, measured in kpc.

In an analysis of H\( \alpha \) emission line maps from 57 typical star-forming galaxies at \( z \sim 1 \), Nelson et al. (2012) reported that H\( \alpha \) emission broadly follows the profile of the stellar continuum but is slightly more extended, such that \( R_e,\text{H}\alpha/R_e,F140W \sim 1.3 \) (Nelson et al. 2012), consistent with the expectations from models of inside-out growth in disk galaxies (see also Nelson et al. 2016). While measuring galaxy structural parameters from the stellar continuum emission may slightly underestimate the effective radius enclosing active star formation, the assumption of a circularized profile could also lead to an overestimation of the true star-forming area of the galaxies, since star formation tends to be concentrated in clumps within galaxy disks (Rubin et al. 2010; Korini et al. 2012). Acknowledging these opposing uncertainties, we determined that the benefit of higher S/N and F140W imaging was sufficient to justify its use in estimating the area of active star formation.

As shown in Figure 12, the distribution in \( \Sigma_{\text{SFR}} \) for our sample of galaxies extends to \( \sim 2 M_{\odot} \text{yr}^{-1} \text{kpc}^{-2} \), in agreement with similar measurements for typical galaxies in this same redshift range (e.g., Nelson et al. 2016). We observe a marginally significant difference between the \( \Sigma_{\text{SFR}} \) distributions for galaxies with and without detected Mg II absorption. The mean \( \Sigma_{\text{SFR}} \) for galaxies matched to a Mg II detection is \( 0.30 \pm 0.06 M_{\odot} \text{yr}^{-1} \text{kpc}^{-2} \), compared to \( 0.14 \pm 0.02 M_{\odot} \text{yr}^{-1} \text{kpc}^{-2} \) for galaxies without a Mg II detection. However, we note that the median of the \( \Sigma_{\text{SFR}} \) distribution is not statistically offset between the galaxies with a Mg II detection \( (0.12 \pm 0.08 \text{yr}^{-1} \text{kpc}^{-2}) \) and those without \( (0.10 \pm 0.02 \text{yr}^{-1} \text{kpc}^{-2}) \). A K-S test confirms that
the difference in the $\Sigma_{SFR}$ distributions for the two populations of galaxies—matched and unmatched to Mg II—is less statistically significant, having only 85% confidence, compared to our findings for the SFR distributions for the same populations, which indicated a statistically significant difference with 99% confidence.

The less pronounced difference we observe in the $\Sigma_{SFR}$ distributions relative to the SFR distributions for galaxies with and without Mg II could be due to the additional uncertainty in the measurement of $\Sigma_{SFR}$, which is introduced when estimating the area of active star formation in the galaxies. We also note that there is a strong empirical correlation between dust content and SFR, stemming from the fact that galaxies with higher SFRs tend to be more massive galaxies, which are more metal-rich. Thus, the fact that our SFR measurements are not dust corrected should lead to a bias in the estimated galaxy SFRs, such that galaxies with higher SFRs will have their rates of star formation more greatly underestimated. This bias effectively reduces the dynamic range of our estimated SFRs and should be expected to flatten any trends we observe with SFR. Future observations with deeper broadband imaging or G141 grism data could be used to improve the estimates of the size of the star-forming regions in these galaxies and help to better resolve any underlying physical differences, if they exist, in the $\Sigma_{SFR}$ of galaxies with and without circumgalactic Mg II absorption.

An examination of the redshift distributions of the galaxies with and without Mg II absorption indicates that the galaxies matched to Mg II skew very slightly toward higher redshift. The mean (median) redshift of galaxies matched to Mg II is $1.19 \pm 0.04$ ($1.23 \pm 0.05$), compared to $1.08 \pm 0.04$ ($1.14 \pm 0.05$) for the galaxies unmatched to Mg II. Given that Mg II detections are associated with galaxies that have higher average SFRs, one might expect a Malmquist bias in a flux-limited sample such as ours, favoring the detection of Mg II-absorbing galaxies at higher redshifts. However, all of the SFRs estimated for all galaxies in both the matched and unmatched samples lie above the stated detection threshold. A physical mechanism could instead explain this small redshift difference, since the redshift number density of strong Mg II absorption lines steeply increases with redshift from $z = 0$ to $z \sim 2$ (Nestor et al. 2005; Zhu & Ménard 2013), as does the average SFR of galaxies (e.g., Hopkins & Beacom 2006).

4.5. Azimuthal Distribution of Mg II Absorption

Outflows containing $T \sim 10^4$ K gas appear to be a common feature of star-forming galaxies (Heckman et al. 1990, 2000; Steidel et al. 1996; Franx et al. 1997; Pettini et al. 2000, 2001; Shapley et al. 2003; Martin 2005; Rupke et al. 2005; Tremonti et al. 2007; Weiner et al. 2009; Erb et al. 2012). In the local universe, large-scale outflows have been observed to propagate parallel to the minor axis of galaxies (e.g., Strickland et al. 2004; Heckman et al. 1990; Lehner & Heckman 1996; Cecil et al. 2001; Strickland & Heckman 2009). If the cold gas is preserved out to large radii, the signatures of these winds are expected to be observable statistically in the azimuthal distribution of circumgalactic gas. The preferential distribution of strong Mg II along the minor axis of star-forming galaxies was first reported in the stacked absorption line profiles of intermediate redshift galaxies in zCOSMOS (Bordoloi et al. 2011). Bouché et al. (2012b) reported an even more striking bimodality in galaxies at $z \sim 0.1$, although, some of this difference could be attributed to the more restrictive selection

![Figure 13](image-url). Azimuthal angle ($\phi$) distribution of background quasar sightlines probing foreground galaxies in our sample. The plot includes galaxies not matched to Mg II absorption (blue), all cases where a galaxy matches to a Mg II detection (red), and a subset of the latter that includes only the matched galaxies with the closest projected separation of all possible pairs (black, filled).
becomes more collimated at impact parameters $\rho \sim 50$ kpc. In those simulations, these collimated winds form under-dense cavities along the minor axis, which are surrounded by a denser pressure front at an opening angle of $40^\circ$–$50^\circ$. This would then produce stronger absorption when the quasar shines through the edge of the cone, consistent with the findings of Schroetter et al. (2015) and Schroetter et al. (2019), and explaining our results as well.

We adopt similar nomenclature proposed by Schroetter et al. (2015), and refer to matches with $\phi > 40^\circ$ as wind pairs—since winds produced during periods of high star formation are expected to flow out in this approximate angular region—while matches at $<40^\circ$ are denoted as inflow pairs, since gas inflowing from the intergalactic medium is likely to be accreted by the galaxy along the major axis. Of the 21 absorber-galaxy pairs in our sample with $\rho < 80$ kpc, 81% are categorized as “wind pairs.” The probability of this observed distribution arising from a uniform angular distribution is less than 4%. The preferential enhancement of Mg II that we find around the minor axes of galaxies in this sample is consistent with observations of late-type galaxies at $z \sim 0.5$ (Kacprzak et al. 2012) and may be explained by gas aligned with the minor axis of galaxies having a higher metal enrichment, as would be expected in the case of star formation-driven outflows propagating perpendicular to the disks of galaxies.

In Figure 14, we show, in bins of projected physical separation, the fraction of wind pairs within the sample of Mg II detections matched to foreground galaxies. We find a significant excess of Mg II detections with $\phi > 40^\circ$ at small impact parameters, which persists out to $\sim 80$ kpc around foreground galaxies. These observations are consistent with those of Schroetter et al. (2019), who recently reported the detection of a bimodal Mg II distribution extending 60–80 kpc around star-forming galaxies at $z \sim 1$.

As shown in Figure 15, the bimodality in the azimuthal angle distribution of all galaxy-absorber matches (not just the closest matches) indeed strengthens when galaxies at impact parameters of $\rho > 80$ kpc are excluded. This observation agrees with the findings of Bordoloi et al. (2014a), who reported that the distribution of Mg II becomes increasingly isotropic at greater impact parameters, potentially indicating an increased contribution from infalling material or satellite galaxies, or the maximum extent of cold gas in star formation-driven outflows.

Theoretical models predict that radiation pressure from galaxies with SFR surface densities of $\Sigma_{\text{SFR}} \gtrsim 0.05 \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$ can drive outflows of $\sim 10^3$ K gas to distances of 50–100 kpc around galaxies (Murray et al. 2011; Hopkins et al. 2012), and there are reasons to expect that the average morphologies of star formation-driven galaxy outflows may evolve over time. In an analysis of the IllustrisTNG simulation, Nelson et al. (2019) claimed that the collimation of outflows around star-forming galaxies emerges between the redshifts $z = 2$ and $z = 1$ and becomes more pronounced at lower redshifts. Simulations of outflows from $L_*$ galaxies in the Feedback In Realistic Environments (FIRE) simulation (Muratov et al. 2015) also predict a weakening of the mass-loading factor of star formation-driven outflows with decreasing redshift, due in part to the deepening gravitational potential well in the center of the average galaxy halo and the lower frequency of gas-rich mergers triggering episodic bursts of star formation. Simulations of star-forming galaxies using the N-body + SPH code GASOLINE (Wadsley et al. 2004) also indicate that the efficiency with which galaxies generate outflows increases with decreasing galaxy mass (Christensen et al. 2016). Thus, we might expect to observe an evolution in both the collimation and extent of outflows around star-forming galaxies in the range of $0 < z < 2$, with outflows extending farther into the halos of galaxies at $z > 1$, compared to at lower redshifts.

Kacprzak et al. (2011b) and Bordoloi et al. (2014a) reported that the bimodality of the azimuthal distribution disappears at $\rho > 40$ kpc at $z \sim 0.5$, while our study—at significantly higher redshift ($z \sim 1.2$)—finds persistent bimodality out to $\rho = 80$ kpc. Combined with the similar findings at $z \sim 1$ from Schroetter et al. (2019), these observational results appear to support theoretical predictions of star formation-driven outflows reaching larger physical distances around galaxies at earlier times.

In Figure 16, we split our galaxy-absorber pairs at the median redshift ($z = 1.2$) into high and low redshift subsamples with median redshifts of $z = 0.92$ and $z = 1.23$, respectively. Plotting the azimuthal distribution of each subsample indicates that the fraction of Mg II absorbers detected with $\phi > 40^\circ$ is marginally greater at higher redshift. Among all of the possible matched galaxy-absorber pairs in our sample 60% (12/20) can be classified as wind pairs at $z < 1.2$, compared to 79% (22/28) at $z > 1.2$. Despite these reasonably small size of these samples, which limits our ability to draw conclusions about the possible redshift evolution in the azimuthal distribution (Figure 16), the large fraction of wind pairs in the higher redshift subsample is significant. A K-S test indicates that the azimuthal distribution of the $z > 1.2$ subsample, which peaks at $55^\circ$, has a < 3% likelihood of being drawn from a random distribution.

In Figure 17 we present the distribution of our galaxy-absorber pairs as a function of the impact parameter and azimuthal angle, color coded separately by Mg II equivalent width ($W_r$) and galaxy SFR. The majority (79%) of galaxies with SFRs above the mean of this sample have Mg II detections at azimuthal angles greater than $40^\circ$, indicating an outflow origin. Interestingly, in contrast to many other lines of evidence linking higher equivalent width Mg II absorbers to star formation-driven outflows, we find no significant correlation between $W_r$ and the azimuthal angle in our sample.

Figure 18 presents the average SFR of galaxies matched to Mg II absorption in bins of impact parameter, separately for wind pairs and inflow pairs. Wind pairs with $\rho \lesssim 80$ kpc have
significantly higher mean galaxy SFRs compared to wind pairs at \( \rho > 100 \) kpc. While the small number of inflow pairs restricts what conclusions can be drawn about their global properties, these data appear to suggest that they may also be associated with lower SFRs compared to wind pairs. A larger sample of inflow pairs would be needed to confirm this possible trend.

Interestingly, despite the bimodality of the azimuthal distribution at \( \rho < 80 \) kpc, which is suggestive of inflows and outflows, a significant fraction of the detected wind pairs have low SFRs. This result could potentially be explained by the sporadic nature of star formation activity; the period of rapid star formation that generated strong winds could have quieted by the time the outflowing gas reaches the quasar sightline. It is also possible that some of these absorbers may have been assigned to galaxies with matching redshifts that are not their primary hosts.

4.6. Modeling Galaxy Contributions to \( W_r \)

Several factors—including the origins of the gas and the properties of its host galaxy—are understood to contribute to the equivalent width of the MgII detected in the CGM of galaxies. Determining the relative effects of the many contributing factors from the equivalent width measurement of a single galaxy-absorber pair may be impossible with one individual detection. However, with a statistical sample of galaxy-absorber pairs for which those contributions are measured, we can develop a model that describes the average expected contribution of each factor to the measured equivalent width.

As previously discussed in Section 4.2, the anticorrelation between \( W_r \) and the impact parameter is well established, but there is considerable scatter around the best-fit trend line (Figure 9). Various properties of the host galaxy (e.g., SFR, azimuthal angle, stellar mass) and its environment have been shown to correlate with \( W_r \) (Chen et al. 2010a; Kacprzak et al. 2011a; Bouček et al. 2012b; Churchill et al. 2013; Nielsen et al. 2013), and are therefore expected to contribute to the scatter in the \( W_r-\rho \) relation.

Our observations provide additional information about the galaxies matched with absorption—namely, the azimuthal
angle and environment—that may allow us to better predict the equivalent width of a galaxy-absorber pair. Using these measurements, we have created a model that adopts the previously established relationship between $W_r$ and the impact parameter at high redshifts (discussed in Section 4.2), while also folding in the observed correlation between $W_r$ and the azimuthal angle. Incorporating SFR information did not significantly improve the predictions of the equivalent width, so we ultimately excluded it from our model. This lack of importance of galaxy SFR may be surprising, because past studies at intermediate redshift (e.g., Zibetti et al. 2007; Ménard et al. 2008; Noterdaeme et al. 2010; Ménard et al. 2011; Bordoloi et al. 2011; Ménard & Fukugita 2012; Bordoloi et al. 2014b; Lan & Mo 2018) have found a strong correlation between $W_r$ and the SFRs of matching galaxies. There are a few possible explanations for this result. Since most $z \sim 1$ galaxies have relatively high SFRs, we could be under-sampling galaxies with low SFRs. In that case, we may be lacking the dynamic range required to accurately model the correlation of SFR with $W_r$. This problem may be further compounded by the lack of dust correction in our SFR estimates, as previously discussed. The small size of our data set could also obscure the contributions of SFR to $W_r$. We note that while stellar mass is also expected to affect the covering fraction and distribution of Mg II absorption, we are currently unable to account for this additional affect.

Figure 19 shows the results of four different models of $W_r$: one that only includes the impact parameter (Section 4.2), one that includes the impact parameter and environmental information, one that takes the impact parameter and the azimuthal angle into account, and a final, three-parameter model (impact parameter, environment, and azimuthal angle). We find that our ability to predict the observed $W_r$ is strengthened when both the azimuthal angle and environmental information are included. This is consistent with findings by Kacprzak et al. (2012), who reported that the azimuthal angle is an important factor in determining a galaxy’s contribution to $W_r$. 

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Figure 17. Observed relation between the azimuthal angle and impact parameter for galaxies matched to Mg II, shown with color denoting the SFR (left) and the rest-frame equivalent width of the 2796 Å Mg II absorption line (right).

Figure 18. Mean SFR of galaxies matched to Mg II absorption, shown as a function of the impact parameter ($\rho$). The data are subdivided by the azimuthal angle, with wind pairs ($\phi > 40^\circ$) and inflow pairs ($\phi < 40^\circ$). Wind pairs with $\rho \lessapprox 80$ kpc have significantly higher mean galaxy SFRs compared to inflow pairs at similar impact parameters and wind pairs at $\rho > 100$ kpc.

Figure 19. Predicted vs. observed $W_r$ of each absorber using three different models. Red shows the model that only takes the impact parameter into account (as discussed in Section 4.2) ($\chi^2 = 16.5$), orange takes the angle and impact parameter into account ($\chi^2 = 5.66$), black includes the effects of the impact parameter and environment ($\chi^2 = 5.17$), while blue includes the effects of all three parameters ($\chi^2 = 4.23$).
In order to match the bimodality observed in the azimuthal distribution (Figure 13), we modeled the correlation between the azimuthal angle and $W_r$ as two Gaussian functions with peaks at $60^\circ$ and $0^\circ$. For galaxies at impact parameters $\rho < 80$ kpc, we model the summed contributions to the Mg II equivalent width as follows:

$$W_r(\rho < 80 \text{ kpc}) = \sum_{k=1}^{n} 10^{a_n \alpha + b_n} \left[ \frac{a_n e^{-\frac{(\phi - 60)^2}{2(\sigma_n)^2}} + b_n e^{-\frac{\phi^2}{2(\sigma_n)^2}}} \right] ,$$

where $\phi$ is the azimuthal angle of the galaxy, $\rho$ is its impact parameter, $n$ is the number of galaxies matched to absorption in the quasar sightline with $\rho < 80$ kpc, $a = -0.003$ and $b = 0.0$, $\alpha_1 = 0.43$ and $\alpha_2 = 0.56$, and the standard deviations of the Gaussian functions are $s_1 = 44.5$ and $s_2 = 43.4$.

Since the distribution of Mg II becomes isotropic at larger impact parameters ($\rho > 80$ kpc), as discussed in Section 4.5, we model the contribution of galaxies at $\rho > 80$ kpc without azimuthal considerations, as follows:

$$W_r(\rho \geq 80 \text{ kpc}) = \sum_{k=1}^{n} 10^{a_n \rho + b_n} .$$

So the total modeled $W_r$ is the summed contribution of all galaxies with impact parameters $\rho < 80$ kpc (Equation (3)) and $\rho \geq 80$ kpc (Equation (4)):

$$W_{\text{total}} = W_r(\rho < 80 \text{ kpc}) + W_r(\rho \geq 80 \text{ kpc}) .$$

This model sums the $W_r$ contributions of all galaxies that are spectroscopically matched to a given absorption feature. It uses the impact parameter to predict the maximum $W_r$ (in Angstroms) contribution of a given galaxy, then uses the azimuthal angle to modify that result. $a$, $b$, $\alpha_1$, $\alpha_2$, $s_1$, and $s_2$ were treated as free parameters in the model and are fit for our data when ultra-strong absorbers ($W_r > 2$ Å) are excluded.

As shown in Figure 20, the model performs worse when ultra-strong absorbers are included. The strongest absorbers are the most likely to have components at very small impact parameters, which may be unresolved from the quasar PSF. Such cases would result in some galaxy-absorber pairs being excluded from the input to the model and could lead to a worse prediction of $W_r$. Galaxies with uncertain redshifts (Table 2), which we have excluded, could also be contributing to the overall scatter about the best-fit parameterization, which worsens for absorbers with $W_r > 2$ Å. The Mg II absorbers modeled in Figure 20 are color coded by the field in which they were detected.

What sets this model apart from previous attempts to understand the relationship between $W_r$ and the impact parameter is the inclusion of both azimuthal angles and environmental information through the summed contributions of all galaxies matched to the absorption. We found that only considering the closest matching galaxy for each absorber, rather than all of the matching pairs, worsened the agreement between the model prediction and the detected $W_r$ (Figure 19). There is potential for this model to be further refined in the future by fitting to a larger sample and by including more precisely determined parameters, such as the dust-corrected SFR and stellar mass.

5. Summary

We have presented first results from an 18-orbit HST program that obtained WFC3/IR G141 grism and F140W direct imaging observations of galaxies around the nine most Mg II-rich quasar sightlines in SDSS. These data have enabled a study of the morphologies, azimuthal angles, SFRs, SFR surface densities, and environments in a large sample of typical Mg II-absorbing galaxies at $0.64 < \Delta z < 1.6$. We were able to measure morphologies for 107 galaxies and SFRs for 98 galaxies. Only one field was fully excluded from our analysis due to the crowding of several galaxies with projected separations of $<5''$ from the quasar, which caused catastrophic contamination in the G141 grism observations.

We report an exceptionally high rate of detection for candidate Mg II host galaxies; 89% (34/38) of the targeted Mg II absorption systems were confidently matched to at least one galaxy with $|\Delta z|/(1 + z_{\text{MgII}}) < 0.006$ within 200 kpc. These observations have helped to expand the limited sample of spectroscopically confirmed Mg II-galaxy pairs at $\Delta z > 1$, which, together with compilations of observations in the literature at lower redshift, indicate a significant redshift evolution in the distribution of Mg II around absorption-selected galaxies.

Nearby half of the absorbers in our targeted sample matched in redshift to two or more galaxies, and the mean Mg II rest-frame equivalent width ($\langle W_r \rangle$) of absorbers matched with groups is greater than that of absorbers matched to isolated galaxies. The sample of galaxies matched to Mg II absorption were found to have a significantly higher mean SFR, and a marginally higher mean $\Sigma_{\text{SFR}}$, compared to galaxies that were not matched to Mg II absorption.
We detect a bimodal azimuthal angle distribution of Mg II around galaxies in our sample. Most of the galaxy-absorber pairs were detected within 50° of the minor axis, suggestive of an origin in star formation-driven outflows. The bimodality of the Mg II azimuthal angle distribution extends to impact parameters of ⟨ρ ∼ 80 kpc⟩, in agreement with other findings of extended Mg II around galaxies at z ∼ 1 (Schröetter et al. 2019) and supporting predictions from recent IllustrisTNG simulations (Nelson et al. 2019). We also find that the signature of wind-driven outflows in the azimuthal angle distribution is more prominent in the higher redshift half of our sample.

Finally, we present a new model that uses the impact parameter, azimuthal angle, and galaxy environment to model the detected W_r of Mg II. The results of our modeling indicates that accounting for the azimuthal angle of the absorption around galaxies and the cumulative effect of multiple galaxies in a group environment results in a better understanding of the detected Mg II equivalent width.

In the future, deeper multiwavelength broadband imaging of these high value fields would enable stellar population synthesis modeling, enabling the further examination of the geometry of Mg II absorption as a function of galaxy age, mass, and virial radius. Such observations would also provide photometric redshift constraints for the galaxies in this sample that lack strong emission lines, facilitating improved certainty in absorber pairing and group membership determinations. Higher resolution spectroscopy of both the galaxies and quasar absorption lines would also be useful for improving the matching of galaxies to absorption line components in group environments.

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13 https://github.com/gbrammer/grizli
