On the CGM Fundamental Plane: The Halo Mass Dependency of Circumgalactic H I

Rongmon Bordoloi1,7, J. Xavier Prochaska2, Jason Tumlinson3,4, Jessica K. Werk5,6, Todd M. Tripp6, and Joseph N. Burchett1

1 MIT-Kavli Center for Astrophysics and Space Research, 77 Massachusetts Avenue, Cambridge, MA 02139 USA; bordoloi@mit.edu
2 UCO/Lick Observatory, University of California, Santa Cruz, CA, USA
3 Space Telescope Science Institute, Baltimore, MD, USA
4 Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD, USA
5 University of Washington, Department of Astronomy, Seattle, WA, USA
6 Department of Astronomy, University of Massachusetts, Amherst, MA, USA

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Abstract

We analyze the equivalent widths of H I Lyα (W1215) absorption from the inner (R ≤ 100 kpc) circumgalactic medium (CGM) of 85 galaxies at z ∼ 0 with stellar masses M* ranging 8 ≤ log M*/M⊙ ≤ 11.6. Across three orders of magnitude in stellar mass, the CGM of present-day galaxies exhibits a very high covering fraction of cool hydrogen gas (fC = 87 ± 4%) indicating that the CGM is ubiquitous in modern, isolated galaxies. When H I Lyα is detected, its equivalent width declines with increasing radius regardless of the galaxy mass, but the scatter in this trend correlates closely with M*. Using the radial and stellar mass correlations, we construct a planar surface describing the cool CGM of modern galaxies: log W1215 = (0.34 ± 0.02) − (0.0026 ± 0.0005) × (R) + (0.286 ± 0.002) × log(M*/M⊙). The rms scatter around this bivariate relation is ~0.2 dex. We interpret the explicit correlation between W1215 and M* to arise from the underlying dark matter halo mass (Mhalo), thereby suggesting a CGM fundamental plane between W1215, R, and Mh. This correlation can be used to estimate the underlying dark matter halo mass from observations of saturated H I Lyα in the CGM of a modern galaxy.

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

1. Introduction

In the original ΛCDM paradigm, gas accreting onto dark matter halos cools, sinks to the center of the halo, and condenses to form stars (White & Rees 1978; Mo & White 1996). Advances in multi-wavelength observations over the last two decades have resulted in a more sophisticated picture of galaxy evolution in which gas and metals cycle into and out of galaxies continually over time. Gas accretion fuels star formation and grows the galaxies. Feedback from supernovae or active galactic nuclei eject gas and metals from galaxies and help to quench star formation (e.g., Somerville & Davé 2015). This baryon cycle takes place in the region surrounding galaxies called the circumgalactic medium (CGM; Chen et al. 2010a; Steidel et al. 2010; Bordoloi et al. 2011, 2014b; Tumlinson et al. 2011, 2017; Nielsen et al. 2013; Werk et al. 2013; Prochaska et al. 2017).

The dominant gravitational potential of dark matter influences halo gas dynamics: it may set the coronal gas temperature, the pressure gradient, and the cooling and cloud-infall timescales (Mo & White 1996). Observations of CGM gas provide an opportunity to study gas dynamics within halos and to understand these influences.

The dependence of metal-line strength on halo in and/or stellar mass has been demonstrated with Mg II ions (Chen et al. 2010b; Bordoloi et al. 2011; Churchill et al. 2013a). However, Mg II absorption is also believed to trace gas inflows and outflows up to ~100 kpc (Bordoloi et al. 2011, 2014a; Kacprzak et al. 2012; Bouché et al. 2013). Strong Mg II is rarely seen at large impact parameters and so cannot be used to constrain halo dynamics further out. Most other saturated metal absorption lines are generally undetected at available limits at R > Rvir/2 (Bordoloi et al. 2014b; Liang & Chen 2014; Johnson et al. 2015). In this work, we investigate the dependence of Lyα absorption on host galaxy mass. Because strong Lyα absorption is observed even beyond the virial radius, it reveals gas properties across the entire halo.

Pioneering work with the Hubble Space Telescope (HST) mapped the projected radial profile (R) of Lyα and other metal lines around low-z galaxies (e.g., Morris et al. 1993; Bowen et al. 1995; Lanzetta et al. 1995). These studies have found that the multiphase CGM is a complex and rich environment with multiple density and temperature phases (Chen et al. 2001; Bowen et al. 2002; Tripp et al. 2008, 2011; Prochaska et al. 2011). In recent years, large galaxy surveys combined with sensitive QSO spectra from the Cosmic Origin Spectrograph have enabled systematic mapping of the CGM around select samples of galaxies (Werk et al. 2012, 2016; Tumlinson et al. 2013; Bordoloi et al. 2014b, 2017; Liang & Chen 2014; Borthakur et al. 2015; Lehner et al. 2015; Burchett et al. 2016; Heckman et al. 2017).

In previous work, with the COS-Halos and COS-Dwarfs surveys, our group has examined the CGM around galaxies at R < 160 kpc in a wide range of diagnostic ions. The COS-Halos survey (Tumlinson et al. 2013) studied the multiphase CGM surrounding 44 galaxies at z ≤ 0.2 with log M*/M⊙ > 10 (Tumlinson et al. 2011; Werk et al. 2012, 2013). The COS-Dwarfs survey (Bordoloi et al. 2014b) studied the multiphase CGM of 43 galaxies at z ≤ 0.1 with 8 ≤ log M*/M⊙ < 10. In this paper, we combine these data sets to gain a view of cool gas traced by Lyα absorption around galaxies spanning three decades in stellar mass. Through-out this work, we adopted a ΛCDM cosmology (Ωm = 0.238, ΩΛ = 0.762, H0 = 73.2 km s⁻¹ Mpc⁻¹, Ωb = 0.0416).

2. Description of the Sample

Detailed descriptions of survey design and sample selection can be found for COS-Halos in Tumlinson et al. (2013) and for
COS-Dwarfs in Bordoloi et al. (2014b). In short, both surveys utilized \( \text{HST}/\text{COS} \) to acquire UV spectroscopy of bright background quasars spanning 1140–1750 Å at \( R \sim 20000 \) and signal-to-noise ratio (S/N) \( \sim 10 \). Both these CGM surveys were designed as “galaxy selected” surveys, where the projected galaxy-quasar pairs are selected based on projected physical separation and known foreground galaxy properties and without any a priori knowledge of gas properties along the line of sight.

The COS-Halos survey was optimized to study highly ionized CGM gas using O vi and other metal-line diagnostics, targeting \( \sim L^* \) galaxies. The COS-Dwarfs survey was designed to target lower mass galaxies \( (8 \lesssim \log M_*/M_\odot \lesssim 10) \) and was optimized to study moderately ionized gas (C IV) and other low ion diagnostics (Bordoloi et al. 2014b). Both the COS-Dwarfs and COS-Halos surveys target lines of sight that are within \( \sim 160 \) kpc from the host galaxies. Owing to the different mass ranges probed, this impact parameter corresponds to \( \sim 0.6 R_{\text{vir}} \) for COS-Halos and \( 1 R_{\text{vir}} \) for COS-Dwarfs. Both surveys cover the H I Ly\( \alpha \) line, which traces both neutral and predominantly ionized gas. The median statistical 1\( \sigma \) uncertainty for Ly\( \alpha \) equivalent widths \( (W_{\text{Ly}\alpha}) \) is \( \sim 25 \) mA. Using their specific star formation rates (sSFR), we divide these galaxies into star-forming (log sSFR \( \leq -10.6 \)) and passive (log sSFR \( > -10.6 \)), respectively.

Both the COS-Halos and COS-Dwarfs surveys were designed to target predominantly isolated galaxies (Tumlinson et al. 2013; Werk et al. 2013; Bordoloi et al. 2014b). In the COS-Halos survey, the galaxies were selected to not have any accompanying galaxies within 1 Mpc of the candidate galaxies (Tumlinson et al. 2013). In COS-Dwarfs, candidate galaxies are selected with SDSS spectroscopic information to have no other galaxies with known redshifts within 300 kpc from the candidate galaxy (Bordoloi et al. 2014b), although a subsample of the galaxies have other galaxies at similar redshifts but at larger separations (0.3–1 Mpc). Hence, this study primarily focuses on the inner CGM properties of isolated galaxies and any effects of galactic environment on the CGM gas are not the focus of this study (see, e.g., Burchett et al. 2016 for the impacts of galactic environment).

3. Results

To map the spatial extent of Ly\( \alpha \) absorption around galaxies, we first investigate the Ly\( \alpha \) covering fraction \( (f_C) \) at different impact parameters around galaxies. We define covering fraction as

\[
f_C = \frac{N_{W_{\text{Ly}\alpha} > \text{cut}}}{N_{\text{tot}}},
\]

where \( N_{W_{\text{Ly}\alpha} > \text{cut}} \) gives the number of galaxies within either an impact parameter or a stellar mass bin, which have associated Ly\( \alpha \) equivalent width \( (W_{\text{Ly}\alpha}) \) greater than some cutoff equivalent width \( W_{\text{cut}} \). \( N_{\text{tot}} \) gives the total number of galaxies in that same bin. Figure 1 shows \( f_C \) as a function of impact parameter (panels (a), (b)) and stellar mass (panels (c), (d)) for \( W_{\text{cut}} \geq 100 \) mA. The binomial confidence intervals on \( f_C \) are reported as Wilson Score 68% confidence intervals.

Throughout this paper, we adopt an equivalent width cutoff of \( W_{\text{cut}} \geq 100 \) mA for \( f_C \) measurements. Figure 1 shows that Ly\( \alpha \) absorption is nearly ubiquitous around both star-forming and passive galaxies out to 160 kpc. Of 85 galaxies, 74 exhibit Ly\( \alpha \) absorption above this cutoff, yielding \( f_C \) of 87 ± 4% for the full sample. Star-forming galaxies exhibit \( f_C \) of 92 ± 4% (55/60) within 160 kpc, and \( f_C \) of 100% (33/33) within 90 kpc. The passive galaxies also exhibit a large \( f_C \) of 76 ± 8% (19/25) within 160 kpc. For \( R < 90 \) kpc, the passive galaxies show a detection rate of 92 ± 8% (11/12).

Figure 1, panels (c) and (d), show the Ly\( \alpha \) covering fraction as a function of galaxy stellar mass. For the full sample, \( f_C \) does not depend on the stellar mass of its host galaxy: 29 out of 33 galaxies at \( \log M_*/M_\odot < 9.75 \) exhibit Ly\( \alpha \) absorption with \( f_C \) of 88 ± 6%, and at \( \log M_*/M_\odot \geq 9.75 \), \( f_C \) is 87 ± 5% (45/52). Among star-forming galaxies at \( \log M_*/M_\odot < 9.75 \), \( f_C \) is 89 ± 6% (25/28), and at \( \log M_*/M_\odot \geq 9.75 \), \( f_C \) is 94 ± 4% (30/32). For passive galaxies at \( \log M_*/M_\odot < 9.75 \) and \( \log M_*/M_\odot \geq 9.75 \), \( f_C \) is 80 ± 17% (4/5) and 75 ± 10% (15/20), respectively.

We conclude that in the CGM of galaxies spanning 3 decades in stellar mass \( (8 < \log M_*/M_\odot < 11.6) \), Ly\( \alpha \) absorption is seen with high incidence for all galaxies. In passive galaxies, its presence at high incidence is a puzzle in light of these galaxies’ low or nonexistent star formation (Thom et al. 2012).

We further investigate variations in Ly\( \alpha \) absorption strength as a function of impact parameter. Panel (a) of Figure 2 shows that the Ly\( \alpha \) absorption strength decreases slightly at higher impact parameters. The observed Ly\( \alpha \) equivalent widths around star-forming galaxies (blue filled squares) and passive galaxies (red filled squares) are shown, respectively. Most of the measured \( W_{\text{Ly}\alpha} \) uncertainties are smaller than the size of the data points. The open squares with arrows show the 2\( \sigma \) upper limits for non-detections. There is a weak anti-correlation between Ly\( \alpha \) equivalent width and impact parameter. A Kendall’s Tau test shows that log \( W_{\text{Ly}\alpha} \) and impact parameter are anti-correlated with a \( P \) value <0.005; this corresponds to ruling out the null hypothesis that there is no correlation between these two quantities at 2.8\( \sigma \) significance. Several studies have shown that the Ly\( \alpha \) equivalent width falls off steeply beyond an impact parameter of \( \sim 300 \) kpc (Wakker & Savage 2009; Prochaska et al. 2011; Johnson et al. 2015). We parameterize this 1D radial profile as a power law. Because the detection rate for Ly\( \alpha \) absorption is very high, we perform this fit only on the detections. This parameterization is given by

\[
\log W_{\text{HI} 1215} = 3.0343 \pm 0.07 - (0.0027 \pm 0.0023) \times R
\]

and is shown as the solid gray line in Figure 2, panel (a). This radial profile is valid even as we add more observations within 200 kpc from other surveys (panel (c), Figure 2) (Prochaska et al. 2011; Keeney et al. 2013; Liang & Chen 2014; Borthakur et al. 2015; Bowen et al. 2016; Burchett et al. 2016). The rms scatter around this purely radial trend is \( \sim 0.3 \) dex.

We now investigate the behavior of the residual Ly\( \alpha \) equivalent width once this 1D radial fit is applied to the data. Here the dependent variable is log \( W_{\text{Ly}\alpha} - \log W_{\text{HI} 1215} \), the individual galaxy’s Ly\( \alpha \) equivalent width minus the fitted value from Equation (1). As there are very few non-detections, from this point onward in the paper, we will focus only on the detections. The top right panel of Figure 2 shows that these residuals increase steadily with a clear trend with increasing
stellar mass, for both star-forming and passive galaxies. That is, more massive galaxies generally lie above the fitted radial trend in Equation (1), while less massive galaxies lie below it.

A generalized Kendall’s tau test can assess the statistical significance of this correlation of residual $W_{\text{Ly}\alpha}$ with stellar mass. We consider all galaxies with detected Ly$\alpha$ absorption and obtain significance ($P = 5.02 \times 10^{-6}$). This low value excludes the null hypothesis that there is no correlation between $W_{\text{Ly}\alpha}$ residual and host galaxy stellar mass at $4.6\sigma$ confidence.

We have fit a line to characterize this dependence:

$$\log W_{\text{Ly}\alpha} - \log \bar{W}_{\text{HI}} = (-1.94 \pm 0.34) \log (M_\star / M_\odot) + (0.199 \pm 0.03) \log (M_\star / M_\odot).$$

This fit is plotted as the gray solid line in the right panels of Figure 2. The correlation is observed even as we add the literature data shown in the bottom panels of Figure 2.

We note that some sightlines around lower mass COS-Dwarfs galaxies probe impact parameters which correspond to higher $R_{\text{vir}}$ as compared to COS-Halos sightlines. The COS-Halos sample extends out to an impact parameter of of $R_{\text{vir}} = 0.62$ while there are nine sightlines in COS-Dwarfs sample with $R > 0.62R_{\text{vir}}$. These are marked with open yellow circles in Figure 2. To test that these sightlines are not biasing the observed correlation, we performed the residual analysis after excluding these nine objects. This reduces the detected sample size from 74 to 69 galaxies. Not surprisingly, most of these objects have lower mass, because these galaxies would have smaller virial radii at the same impact parameter as the high-mass systems.

Figure 1. Ly$\alpha$ covering fraction ($W_{\text{Ly}\alpha} > 100 \text{mA}$) as a function of observed impact parameter (top panels) and galaxy stellar mass (bottom panels), respectively. Both the star-forming (left panels, blue shaded region) and passive (right panels, red shaded region) galaxies show high incidence of Ly$\alpha$ absorption. The width of the shaded regions represents Wilson Score 68% confidence interval on $f_C$. The bins along x-axes were chosen to have approximately similar number of galaxies per bin.
We perform a generalized Kendall’s Tau test to assess the statistical significance of the correlation between stellar mass and residual $W_{\text{Ly}\alpha}$, after removing these high $R_{\text{vir}}$ sightlines. We find that a significant correlation exists between stellar mass and residual $W_{\text{Ly}\alpha}$ with a $P$ value $= 4.4 \times 10^{-4}$. This low value allows us to exclude the null hypothesis that there is no correlation between $W_{\text{Ly}\alpha}$ residual and host galaxy stellar mass at $>3.5\sigma$ confidence. We also searched for any possible trends of $W_{\text{Ly}\alpha}$ residual equivalent widths with the sSFR of the host galaxies and found no statistically significant trend ($P = 0.93$).

The mass dependence of $W_{\text{Ly}\alpha}$ can be better visualized in Figure 3 (left panel), which shows the $W_{\text{Ly}\alpha}$ radial absorption profile color-coded by their stellar mass. The high-mass galaxies trend toward higher equivalent widths at all impact parameters, visually indicating a dependence with stellar mass.

This analysis suggests that $W_{\text{Ly}\alpha}$ can be described primarily as a function of two variables: the impact parameter and the stellar mass of the host galaxy. We quantify this dependence by fitting a surface to the $\text{Ly}\alpha$ absorption strength as a function of stellar mass and impact parameter, given as

$$
\log W_{\text{HI 1215}}^s = (0.34 \pm 0.02) - (0.0026 \pm 0.0005) \times (R) \\
+ (0.286 \pm 0.002) \times \log(M_*/M_\odot).
$$

Figure 3 (right panel) shows the surface fit to the COS-Halos and COS-Dwarfs data. The inset shows the residual $\text{Ly}\alpha$ equivalent widths for star-forming (blue) and passive (red) galaxies, respectively. The surface fit characterizes well the $\text{Ly}\alpha$ absorption around star-forming galaxies, yielding an rms scatter $\sim0.18$ dex. The inset of Figure 3 (right panel) shows this distribution of residuals around the fitted two-dimensional (2D) plane. Equation (3) is used for both star-forming and passive galaxies and can describe the $\text{Ly}\alpha$ absorption strength around...
galaxies spanning a mass range of $8 \leq \log M_*/M_\odot \leq 11.6$. For passive galaxies, this surface fit shows a modestly higher scatter (0.29 dex). The slightly higher scatter could be caused by two different factors. First, higher mass passive galaxies are in general seen in over-dense regions and might be tracing group environments. Hence there might be other unforeseen environmental effects which increase the scatter (Burckett et al. 2018). Second, it is possible that the slope of the surface fit is different for star-forming and passive galaxies. Since our sample is dominated by star-forming galaxies, they drive the fit in Equation (3). This could be another reason for the increased scatter in the residual Ly$\alpha$ equivalent widths of passive galaxies. The sample size of passive galaxies in this work is not adequate to explore these. We will analyze this issue in a future study.

4. The Dynamics of the Cool CGM Gas

Because the observed Ly$\alpha$ absorption of the inner CGM is primarily saturated (i.e., the peak optical depth $\tau_{Ly\alpha} \gg 1$), the $W_{Ly\alpha}$ values are likely a better measure of bulk kinematics rather than the column density of the gas. The velocity centroids and ranges of Ly$\alpha$ absorbers in the COS-Halos and COS-Dwarfs surveys are generally consistent with being bound to their host dark matter halo even when projection effects are accounted for (Tumlinson et al. 2013, R. Bordoloi et al. 2018, in preparation), but this does not by itself explain the scaling with $R$ and $M_*$ observed here.

We examine the hypothesis that $W_{Ly\alpha}$ traces the halo gravitational potential in a simple model. We make an ansatz that the trend of increase of Ly$\alpha$ residual equivalent width with increasing stellar mass is owing to higher velocity dispersion of the gas in higher mass dark matter halos. This ansatz is only valid for saturated absorbers in the flat portion of the curve of growth. Any unsaturated absorbers trace the underlying H$\alpha$ column density rather than bulk gas kinematics and will add to the scatter seen in Figure 2 panels (b), (d), but we note that Ly$\alpha$ saturates at an equivalent width of $\approx 0.1$ Å. Additionally, if a saturated Ly$\alpha$ line transitions to the damped part of the curve of growth (e.g., for Damped Ly$\alpha$ absorbers), then the $W_{Ly\alpha}$ reflects the associated column density rather than the velocity dispersion. Such absorbers will also add to the scatter seen in Figure 2 panels (b), (d). However, most of the H$\alpha$ column densities associated with COS-Halos galaxies (Prochaska et al. 2017) are not high enough to produce strong damping wings, and no Ly$\alpha$ absorption profile associated with COS-Dwarfs galaxies exhibit damping wings (R. Bordoloi et al. 2018, in preparation). We assume that each halo possesses an NFW density profile (Navarro et al. 1996) and a halo mass given by fitting abundance matching relations as described in Tumlinson et al. (2013), and Bordoloi et al. (2014b). For each galaxy, we compute the associated velocity dispersion ($\sigma$) at the given impact parameter ($R$) for its halo mass. For any Ly$\alpha$ absorber present in the CGM of that galaxy, the Doppler $b$ parameter is assumed to be $b = \sqrt{2} \sigma$. Then from a curve of growth, the expected Ly$\alpha$ equivalent width ($W_{\text{model}}(R, N, b)$) is computed, for a column density ($N$) and Doppler $b$ parameter. We stress that this model is not sensitive to column density for any saturated absorber in the flat portion of the curve of growth. We have well constrained H$\alpha$ column density measurements for the COS-Halos galaxies (Prochaska et al. 2017), and we use the apparent optical depth H$\alpha$ column density estimates for COS-Dwarfs galaxies. The expected residual Ly$\alpha$ equivalent width values for this model is given as $\log W_{\text{model}} - \log W_{\text{HI}1215}$. Where $\log W_{\text{HI}1215}$ is given by Equation (1). Figure 4, left panel shows the residual distribution for each sightline in this model (star symbols). The blue and red points are the Ly$\alpha$ residual distribution as shown in Figure 2, panel (b). The predictions from this simple model qualitatively reproduce the trend of enhanced $W_{Ly\alpha}$ with increasing stellar mass of the host galaxies.

To estimate the associated model uncertainties, we perform a suite of Monte Carlo simulations as follows. The main source of uncertainty involved in this simple model comes from the uncertainty in halo mass estimates, uncertainty in H$\alpha$ column density estimates, and uncertainty in $\log W_{\text{HI}1215}$. These

Figure 3. Left panel: the radial profile of Ly$\alpha$ absorption for the same galaxies, color-coded with their stellar mass. The higher mass galaxies typically segregate toward higher equivalent widths at all impact parameters. Both panels are showing data from this work only. Right panel: a surface fit showing the Ly$\alpha$ absorption within 160 kpc of the host galaxies across three decades of stellar mass. At a given stellar mass and impact parameter, the Ly$\alpha$ absorption strength can be predicted by the slope of this surface. The inset shows the residual equivalent widths of the fit for the whole sample.
uncertainties propagate in a nonlinear fashion. To account for
all these uncertainties, we conservatively assume that the halo
mass estimates have a 10% uncertainty of 1 dex associated with
them. These are conservative numbers as typical abundance
matching halo mass uncertainties are ~0.2–0.3 dex (Behroozi
et al. 2010). We also conservatively assume that the H I column
densities are uncertain by 2 dex. The uncertainty in log $W_{\text{HI}1215}$
is given in Equation (1). The model was regenerated 10000
times, while randomly including these uncertainties. This gives
a distribution of $W_{\text{Ly}a}$ residuals for each galaxy. The width
of this distribution is representative of model uncertainty
associated with each galaxy. We take the width containing
68% of the distribution as the estimation of model uncertainty.
This is shown as gray error bars in Figure 4, left panel. It is
clear that, even after accounting for conservative model
uncertainties, the trend of increasing residual $W_{\text{Ly}a}$ with stellar
mass is well reproduced by this simple model. We conclude
that the increase in $W_{\text{Ly}a}$ with stellar galaxy mass at the inner
CGM is primarily driven by the gas kinematics in the CGM.
The cool gas clouds are plausibly bound to the dark matter
halos of the host galaxies and are essentially tracing their
dynamics.

Thus, Ly$\alpha$ absorption strength, impact parameter and the
host dark matter halo mass form a fundamental plane. By fitting
the observations of COS-Halos and COS-Dwarfs galaxies, we
characterize this “CGM fundamental plane” as follows:

$$\log W_{\text{HI}1215} = \alpha_1 + \alpha_2 R + \alpha_3 \log(M_{\text{halo}}/M_\odot).$$

The best-fit coefficients with 95% confidence bounds are found
to be $\alpha_1 = -0.45 (-1.7, 0.8)$, $\alpha_2 = -0.004 (-0.005, -0.002)$,
and $\alpha_3 = 0.31 (0.2, 0.4)$, respectively.

In this formulation, the dependence on $R$ is quite weak and
halo mass is the dominant factor. As a consequence of this halo
mass effect, this fit is reversible as an estimator for halo mass.
The halo mass estimations derived from Ly$\alpha$ absorption
equivalent widths at different impact parameters are shown as
dashed lines in the right panel of Figure 4. The data points are
a combined sample of archival surveys (as in Figure 2, panel (c)),
for which halo mass estimates are available. The points are
colored coded to show different impact parameter ranges. The
high and low impact parameter Ly$\alpha$ absorbers clearly segregate
away from each other in equivalent width halo mass plane. This
simple empirical fit given in Equation (4) allows us to estimate
halo masses from any CGM observations of isolated galaxies,
simply knowing the equivalent width and impact parameter of a
Ly$\alpha$ absorber.

The uncertainty on this halo mass estimator will come from the
uncertainty introduced while fitting Equation (4). Some of the
uncertainty will come from the abundance matching halo masses
used to create this fit. Another source of uncertainty is the intrinsic
scatter seen around the surface fit (Figure 3, right panel). This
may come from secondary macroscopic effects such as the
environment in which the host galaxy resides (Burchett et al.
2016). Alternatively, higher column density H I is also known to
be associated with galaxy processes (e.g., accretion or extended
disks for Damped Ly$\alpha$ absorbers), which will add to the
uncertainty associated with this halo mass estimation method.

We can also assess the typical uncertainty associated with this
halo mass estimator by using $W_{\text{Ly}a}$ observations around two
individual galaxies where multiple lines of sight pass through
their CGM (Keeney et al. 2013; Bowen et al. 2016). Keeney
et al. (2013) probe the CGM of a galaxy with halo mass log
$M_{\text{halo}}/M_\odot \sim 10.6–11.4$, at three impact parameters ($R =
74, 93$ and 172 kpc). Using their $W_{\text{Ly}a}$ values, we derive a
mean halo mass log $M_{\text{halo}}/M_\odot \approx 10.8 \pm 0.3$. Similarly, Bowen
et al. (2016) studied the CGM around a single galaxy (halo
mass log $M_{\text{halo}}/M_\odot \sim 12 \pm 0.2$), using four sightlines ($R =
48–165$ kpc). We again use their $W_{\text{Ly}a}$ measurements to derive a
mean halo mass log $M_{\text{halo}}/M_\odot \approx 11.5 \pm 0.67$. Both of these
elements highlight the reasonable accuracy with which this new
method can estimate the halo mass of a system. Detailed future
work will test and better constrain these uncertainties by
comparing such observations and halo mass estimators with
simulations. Such empirical scaling relations provide crucial
independent constraints to estimate dark matter halo mass from
observed gas dynamics.

In recent years, it has been convincingly shown that there is a
correlation between Mg II equivalent width with halo and/or
stellar mass (Chen et al. 2010b; Bordoloi et al. 2011; Churchill

Figure 4. Left panel: comparison of residual Ly$\alpha$ equivalent widths with stellar mass as in Figure 2. The stars show the Ly$\alpha$ equivalent width traces the same kinematics as their host galaxy’s dark matter halos. Right panel: halo mass estimates for Ly$\alpha$ absorption seen at different impact parameters are shown as dashed lines. The observed data points trace these halo mass estimates with reasonable accuracy.
et al. 2013a, 2013b; Zhu et al. 2014). In Particular, Churchill et al. (2013a, 2013b) showed that a strong correlation exists between Mg II absorption equivalent width and virial radius normalized impact parameter of an absorber. Such a correlation is also seen for other metal lines probing CGM of galaxies at different masses (e.g., Bordoloi et al. 2014b; Liang & Chen 2014; Prochaska et al. 2014; Johnson et al. 2015; Burchett et al. 2016). Churchill et al. (2013b) found that, Mg II absorption strength is determined by the virial mass of the host dark matter halo, while most of the Mg II absorption resides at close impact parameter. However, at close impact parameters, strong Mg II absorption also trace gas inflows and outflows (Bordoloi et al. 2011; Kacprzak et al. 2012; Bouché et al. 2013; Bordoloi et al. 2014a). Such galactic origins of metal lines make it hard to use them as tracers of halo dynamics alone. Moreover, strong MgII is rarely seen at large impact parameters and so cannot be used to constrain halo dynamics further out. Incidence of other strong saturated metal absorption lines are generally low at $R > R_{vir}/2$ (Bordoloi et al. 2014b; Liang & Chen 2014; Johnson et al. 2015). Lastly, metallicity would certainly play a (nonlinear) role in any such relation and may increase the observed scatter.

We stress that this result is only valid for saturated Lyα absorbers on the flat part of curve of growth, observed within 200 kpc of their host galaxies. Moreover, this analysis, as noted in Section 2, is focused on relatively isolated galaxies. Recent studies have shown that circumgalactic Lyα absorption is very weak (or absent altogether) in clusters (Burchett et al. 2018) and in some merging galaxies (Johnson et al. 2014).

Equation (4) may not apply to the CGM in those environments.

5. Summary

In this work, we present the variation of Lyα absorption strength in the CGM of 85 galaxies from the COS-Halos and COS-Dwarfs surveys. All measurements are within 160 kpc from the host galaxies and the galaxies span a mass range of $8 \leq M_*/M_\odot \leq 11.6$. The main findings of this work are as follows.

1. Across three decades in stellar mass, Lyα absorption with $W_{1,1,0} > 100 \text{ m\,A}$ is ubiquitous around both star-forming (blue points) and passive (red points) galaxies out to 160 kpc.

2. After accounting for the radial dependence, the residuals of Lyα absorption show a strong trend of increasing Lyα equivalent width with increasing stellar mass of the host galaxy. A generalized Kendall’s tau test rules out the null hypothesis that no correlation exists between Lyα absorption strength and the host galaxy stellar mass at $4.6\sigma$ confidence ($P = 5.02 \times 10^{-4}$).

3. This strong correlation persists, even after removing nine high $R_{vir}$ sightlines. For this sample, a generalized Kendall’s tau test rules out the null hypothesis that no correlation exists between Lyα absorption strength and the host galaxy stellar mass at $>3.5\sigma$ confidence ($4.4 \times 10^{-4}$).

4. The bi-variant dependence of Lyα equivalent widths with impact parameter and host galaxy stellar mass can be characterized by a surface fit given in Equation (3). The surface can characterize the Lyα absorption strength around a star-forming galaxy with a scatter of $\sim 0.18$ dex and that around a passive galaxy with a scatter of $\sim 0.29$ dex.

This simple empirical relation can be used to directly compare observations with theory and would help constrain numerical simulations. 5. The strong correlation of enhanced Lyα equivalent widths with increasing stellar mass of the host galaxy may be driven by dynamics of the gas. A simple model that assumes that the increase in equivalent width is proportional to the velocity dispersion of the host dark matter halo can explain the observed trend remarkably well. This suggests that such Lyα absorbers are typically bound to the dark matter halo of the host galaxy and are generally tracing the dynamics of the halo itself. 6. The observed Lyα absorption in the inner CGM traces the host dark matter halo properties. Lyα absorption strength, projected distance from the galaxy, and mass of the host dark matter halo form a “CGM fundamental plane”, which allows us to estimate the host dark matter halo mass from simple observations of Lyα absorption along a line of sight.

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ORCID iDs

Rongmon Bordoloi https://orcid.org/0000-0002-3120-7173
J. Xavier Prochaska https://orcid.org/0000-0002-7738-6875
Jason Tumlinson https://orcid.org/0000-0002-7982-412X
Jessica K. Werk https://orcid.org/0000-0002-0355-0134
Todd M. Tripp https://orcid.org/0000-0002-1218-640X

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