ON THE SIZE AND MASS OF PHOTOIONIZED CLOUDS IN EXTENDED SPIRAL GALAXY HALOS

JULIE D. DAVIS, BRIAN A. KEENEY, CHARLES W. DANFORTH, AND JOHN T. STOCKE

Center for Astrophysics and Space Astronomy, Department of Astrophysical and Planetary Sciences, University of Colorado 389 UCB, Boulder, CO 80309, USA;
julie.davis@colorado.edu

Received 2015 April 20; accepted 2015 July 29; published 2015 September 2

ABSTRACT

The size and mass of two circumgalactic medium (CGM) clouds in the halo (impact parameter = 65 kpc) of a nearby late-type galaxy, MGC-01-04-005 (cz = 1865 km s⁻¹), are investigated using a close triplet of QSO sight lines (the “LBQS Triplet”). Far ultraviolet spectra obtained with the Cosmic Origins Spectrograph on board the Hubble Space Telescope find two velocity components in Lyα at ~1830 and 1900 km s⁻¹ in two of these sight lines, requiring minimum transverse cloud sizes of ≥10 kpc. A plausible, but not conclusive, detection of C IV 1548 Å absorption at the higher velocity in the third sight line suggests an even larger lower limit of ≥23 kpc for that cloud. Using various combinations of constraints, including photoionization modeling for one absorber, lower limits on masses of these two clouds of ≥10⁶ Mₖ are obtained. Ground-based imaging and long-slit spectroscopy of MCG-01-04-005 obtained at the Apache Point Observatory 3.5 m telescope find it to be a relatively normal late-type galaxy with a current star formation rate (SFR) of ~0.01 Mₖ yr⁻¹. GALEX photometry finds an SFR only a few times higher over the last 10⁸ years. We conclude that the CGM clouds probed by these spectra are typical because they are at impact parameters of 0.4–0.5 Rₘₖ from a rather typical, non-starbursting late-type galaxy; thus, these size and mass results should be generic for this class. Therefore, at least some CGM clouds are exceptionally large and massive.

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

1. INTRODUCTION

In the last few years, the advent of the high throughput far-ultraviolet (far-UV) Cosmic Origins Spectrograph (COS; Green et al. 2012) on the Hubble Space Telescope (HST) has allowed the discovery of a massive and extensive circumgalactic medium (CGM, a.k.a. a gaseous halo) around late-type galaxies (Prochaska et al. 2011; Tumlinson et al. 2011, 2013; Borthakur et al. 2013; Stocke et al. 2013, 2014; Werk et al. 2013, 2014; Bordoloi et al. 2014; Lehner et al. 2015). COS FUV spectroscopy of background, bright QSO targets finds that H i is often accompanied by low- (e.g., C ii, Si ii, Si iii) and/or high-ion (e.g., C iv, Si iv, and O vi) metal absorption lines at the redshifts of foreground, typically late-type galaxies. The absorptions occur ubiquitously within approximately one projected virial radius (Rₘₖ; see Shull 2014, for a detailed discussion) implying a high covering factor (Prochaska et al. 2011; Tumlinson et al. 2011; Stocke et al. 2013) for the CGM around late-type galaxies in the current epoch.

Studies of low-z galaxy halos have been made by targeting QSO/galaxy pairs using HST/COS (Stocke et al. 2013; Tumlinson et al. 2013; Bordoloi et al. 2014). Using COS science team Guaranteed Time Observations (GTO), Stocke et al. (2013) studied late-type galaxy halos from extreme dwarfs and low surface brightness galaxies to ~Lₙ* spirals at impact parameters ≤1.5 Rₘₖ finding associated H i Lyα absorption in all cases. The COS-Halos research team (Tumlinson et al. 2011, 2013; Werk et al. 2013; Bordoloi et al. 2014) studied both late-type, star forming galaxies and early-type galaxies with very low amounts of current star formation. The first COS-Halos studies were of L > Lₙ* galaxies. The later work of Bordoloi et al. (2014) concentrated on L = 0.1–1 Lₙ* late-type galaxies along with a few lower luminosity dwarfs. The COS-Halos program targeted sight lines whose impact parameters are ≤0.5 Rₘₖ.

These new HST/COS observations were supplemented by the use of archival Space Telescope Imaging Spectrograph (STIS) FUV spectroscopy for a large number of very bright, low-z QSOs in conjunction with ground-based spectroscopic surveys of galaxies near these sight lines (Morris et al. 1993; Bowen et al. 1997; Tripp et al. 1998; Penton et al. 2002, 2004; Stocke et al. 2006, 2013; Prochaska et al. 2011). Differing from the targeted surveys mentioned in the previous paragraph, these “serendipitous” studies found absorption systems first, then identified associated galaxies in some cases using the ground-based galaxy redshift surveys. In these “serendipitous” surveys, approximately 50% of absorbers with log N_Lyα (cm⁻²) ≥ 14.0 are found within the virial radius of an associated galaxy. This percentage decreases with decreasing column density.

These two types of studies (summarized in Stocke et al. 2013) show H i Lyα absorption at comparable redshifts to foreground L > 0.1 Lₙ* late-type galaxies near unity covering a factor out to 1–2 Rₘₖ. Dwarfs also have significant associated absorption but at lesser (~50%) covering factors within 1–2 Rₘₖ. At all luminosities, these covering factors decline quite slowly out to several virial radii, making it unclear where the CGM ends and the IGM begins if only Lyα is considered. However, it has been known for some time (e.g., Chen et al. 2001; Stocke et al. 2006) that metal absorption (C iv and O vi in particular) truncates rather dramatically at ~0.3–1 Mpc from the nearest bright galaxy. It is plausible, but not proven, that metal-enriched gas at Z > 0.1 Zₜoccurs only within the confines of spiral-rich galaxy groups (Stocke et al. 2014), which have similar physical extents to this enriched gaseous reservoir. The detection of extensive CGMs around early-type galaxies remains controversial (Thom et al. 2012).

From the initial COS-Halos program results (Tumlinson et al. 2011) it was already clear that these gaseous halos are very massive. However, determining a more accurate mass in
photoionized halo clouds requires some simple modeling to determine the ionization state, density, and extent of these clouds. This standard photoionization modeling has been accomplished by two independent groups who find quite similar but not identical results. Both analyses assume single phase clouds in photoionization equilibrium with the extragalactic ionizing radiation, whose amount is fixed assuming the value from Haardt & Madau (2012). If a UV background intensity somewhat stronger than that of Haardt & Madau (2012) is used (see Shull et al. 2015, for a justification for this adjustment), the cloud densities and total masses determined would also increase by a similar factor. By determining the ionization parameter using the line ratios of metal ions in different ionization states, total cloud densities and indicative sizes can be calculated. Cloud masses follow by assuming quasi-spherical clouds. Stocke et al. (2013) analyzed 25 systems with at least two adjacent ion states, finding cloud densities and line-of-sight sizes of $n_\text{H} = 10^{-3}$--$10^{-4}$ cm$^{-3}$ and 0.1--20 kpc, respectively. Werk et al. (2014) analyzed the metal absorption systems in 44 clouds finding somewhat lower densities ($n_\text{H} = 10^{-4.2}$ cm$^{-3}$) and larger cloud sizes. However, based on the limited number of input spectral line strengths (and their substantial uncertainties) as well as the unlikely assumption that the clouds are homogenous, single-phase gas, the results of these photoionization models are quite uncertain. Even in ideal circumstances, these models provide only a substantial range for values of cloud density and size (and thus mass). Therefore, other cloud size constraints are required to be able to conclude more definitively that photoionized CGM clouds are large and massive.

From these basic results, the inferences derived for the mass of the CGM around a typical $L \geq 0.1 L^*$ late-type galaxy diverge somewhat between these two studies. Werk et al. (2014) advocate for a single-phase CGM with density decreasing only very slowly away from the associated galaxy and $M_{\text{CGM}} = 6.5 \times 10^{10} M_\odot$. Stocke et al. (2013) use their 25 observed clouds to construct an ensemble mass ($\sim 10^{10} M_\odot$) and a volume filling factor of 3%--10%. The latter results yield a significantly lower total CGM mass, leaving a large volume in the CGM unfilled by photoionized gas clouds.

Whether the CGM is completely filled with photoionized gas or not makes a difference for the interpretation of the detection of O VI absorption. In the Werk et al. (2014) analysis, the O VI must arise in gas co-mingled with the gas giving rise to the photoionized absorption regardless of whether the O VI itself is photoionized or collisionally ionized. In the Stocke et al. (2013) picture, the photoionized clouds are surrounded by a hotter medium which fills 90%--97% of the CGM volume; the interface between the clouds and a hot substrate create the collisionally ionized O VI through shocks. Stocke et al. (2014) claim that broad, shallow O VI absorption discovered in high-signal-to-noise ratio (S/N) COS spectra obtained by the GTO team (Savage et al. 2014) is evidence for this hotter substrate. Unlike the stronger, narrower O VI detected and studied by the COS-Halos Team, this shallower absorption suggests temperatures in the $T = 10^5$--$10^6$ K range. An intra-group gas at these temperatures was predicted to be present in spiral-rich groups by Mulchaey et al. (1996), analogous to the hot gas seen in rich clusters and elliptical-dominated rich groups of galaxies (Mulchaey 2000).

New constraints on cloud sizes can distinguish between these two pictures of the CGM, indirectly arguing for or against a very massive, hot, diffuse group gas surrounding these late-type systems. More generally, since the mass of a quasi-spherical cloud scales as cloud size $r^3$ while the total area of the cloud goes as $r^2$, the larger the individual halos clouds, the greater their mass, scaling as $r^3/r^2$ in the limit of unity covering factor.

In this paper, we place constraints on the size of two halo clouds found around a rather normal $\sim 0.1 L^*$ galaxy using a triple of sight lines closely spaced on the sky (10--23 kpc separation at the galaxy’s Hubble distance of 27 Mpc; see Figure 1). These three closely spaced QSOs were found in the Large Bright QSO Survey (LBQS; Foltz et al. 1987), designated LBQS 0107--025A,B and LBQS 0107--0232 (referred to collectively as the “LBQS triplet” hereafter) and described in detail in Crighton et al. (2010). In Section 2, we describe the HST/COS spectra, concentrating on absorptions found in the three sight lines at $z = 0.00622$. In Section 3, we describe our new observations of galaxy MCG-01-04-005 which bear on its recent star formation history. The discussion in Section 4 focuses on the constraints on cloud size obtained using these observations. In Section 5, we summarize our conclusions.

2. HST/COS FUV SPECTROSCOPY OF THE LBQS TRIPLLET

Crighton et al. (2010) use the absorption line data from the HST/COS FUV spectra of the LBQS triplet to constrain the relationship between galaxies and absorbers at $z < 1$, finding an excess of groups of galaxies compared to expectations. A high column density Lyman limit system (LLS) is present in LBQS 0107--0232 (J0107C hereafter) at $z = 0.557$ and a metal-enriched absorber is found in LBQS 0107--025A,B (J0107A and J0107B hereafter, respectively) at $z = 0.227$, located 200 kpc from a bright galaxy at the same redshift (see Figure 1). Muzahid (2014) used the common O VI absorptions in this system to infer that the O VI-absorbing gas is very large on the sky (600--800 kpc) and must therefore contain a substantial amount of mass ($\gtrsim 10^{11} M_\odot$). This inferred mass is similar to the amount inferred by Stocke et al. (2013) to be in the hot CGM phase found by Savage et al. (2014) and Stocke et al. (2014). Muzahid (2014) also analyzed the photoionized phase in the $z = 0.227$ absorber, finding evidence that this cooler cloud is quite small ($< 1$ kpc), suggesting that it is a high velocity cloud imbedded in the hot O VI-absorbing substrate.

The same COS spectra used by Crighton et al. (2010) and Muzahid (2014) were used by this project. All targets were observed with the COS as part of HST program 11585 (PI: Crighton) in late 2010 and early 2011. J0107A and J0107B were observed with both far-UV, medium resolution gratings COS/G130M (1135 $\lambda < 1450$ Å) and COS/G160M (1400 $\lambda < 1795$ Å). J0107C was observed in the COS/G160M grating only due to the LLS discussed above. Observations made at several different grating positions give continuous spectral coverage over the range 1135 $\lambda < 1795$ Å (1400 $\lambda < 1795$ Å for J0107C) at an approximate resolution of $R = \lambda/\Delta \lambda \approx 18,000$ ($\Delta \lambda \approx 17$ km s$^{-1}$).

The calibrated, one-dimensional spectra for each exposure were obtained from the Mikulski Archive for Space Telescopes (MAST). The individual exposures were then coadded using standard IDL procedures described in detail by Danforth et al. (2010). Briefly, the individual exposures were binned by three pixels, cross-correlated around strong Galactic absorption
features, interpolated onto a common wavelength scale, and combined using an exposure-weighted coaddition scheme. The combined spectra shows the expected smooth continuum and narrow absorption features. The data quality varies over the spectral range due to the different sensitivities and exposure times in the two detectors. Total exposures times, median S/N per resolution element, and median flux levels for each grating are given in Table 1.

2.1. Absorption Line Analysis

To establish the extent of the circumgalactic halo clouds around MCG-01-04-005 (systemic radial velocity = 1864 ± 5 km s⁻¹; Koribalski et al. 2004), we utilize the presence or absence of H I Lyα and C IV 1548, 1550 Å absorption at the host galaxy redshift in the LBQS triplet (see Figure 2 for all detected absorbers at the redshift of MGC-01-04-005).

The H I Lyα absorptions in J0107A and J0107B are best fit using two components (see Table 2). In velocity space, both sight lines include a component at ~1830 km s⁻¹ and one at ~1900 km s⁻¹. The specific values for these fits can be seen in Table 2. All of the line fits have physically reasonable b-values except for the 1836 km s⁻¹ component in J0107B, which is weak enough that a broader, physically plausible, profile is possible within the statistical errors (see Figure 2). Full line profiles based on the Voigt fit parameters in Table 2 are over-plotted as thick solid lines for all absorption features. For the Lyα profiles, the dotted lines indicate the Voigt fits for each component; for the C IV profiles, the thin lines indicate the 1σ uncertainty on these fits. Special care is required when inferring H I column densities from Voigt profile fits to Lyα profiles; we address these concerns in Section 4.1.

The wavelengths of Lyα and C II in J0107C are obscured by a strong, higher redshift LLS. However, in this case, a reasonably strong C IV absorption is visible at ~6σ in the stronger of the two doublet lines (see Figure 2 third column and Table 2). The velocity of the C IV in J0107C corresponds to the weaker line of the CIV doublet is blended with Galactic ISM absorption shown at a velocity of ~72 km s⁻¹ in Figure 2. We modeled out the neutral...
Galactic carbon by simultaneously Voigt-fitting other C\textsc{i} transitions in the same spectrum to obtain a C\textsc{i} column density. A model C\textsc{i} profile using the parameters obtained was then subtracted from the blended region of interest. This model has already been removed from the spectra presented in Figure 2. The location of the C\textsc{i} wavelength is noted in the third row of Figure 2.

In J0107B, only a 3\sigma upper limit on C\textsc{iv} is reported after the C\textsc{i} model was removed. For J0107A and J0107C, we were able to cleanly model the C\textsc{iv} 1548 Å line (a 6\sigma detection). Particularly for J0107A (see Figure 2), the 1548 Å-derived model seems to fit the de-blended 1550 Å feature, implying that the de-blending process was reasonably successful with only small C\textsc{i} residuals. However, this line more than likely contains additional contaminants besides C\textsc{i}, making its parameters less well-determined; i.e., the 1550 Å detection appears too strong for the observed 1548 Å line strength. Table 2 thus lists proxy values for the C\textsc{iv} 1550 Å feature in J0107A based on the values obtained from the 1548 Å measurement.

In J0107C, only the stronger C\textsc{iv} line is well-measured at 1560.9 Å due to the presence of Ly\alpha forest lines at other redshifts in the region of the weaker doublet line. Nevertheless, after the C\textsc{i} de-blending, a weak C\textsc{iv} 1550 Å feature does seem to be present between two strong Ly\alpha absorbers. This tentative detection of the weaker C\textsc{iv} doublet line in J0107C is suggestive, but not conclusive, due to the higher redshift Ly\alpha lines in its vicinity.

With no other definite lines than the C\textsc{iv} 1548 Å identification at the same redshift in J0107C, we must entertain the possibility that this line is actually a spurious, weak feature at a different redshift. Ly\alpha absorbers are by far the most common in the IGM so the alternative interpretation of the 1560.9 Å feature as Ly\alpha at z = 0.284 is suggested. The line has an observed equivalent width of $W = 96 \pm 44$ mÅ with a fitted $b = 34 \pm 11$ km s$^{-1}$. Interpreted as a weak Ly\alpha absorber on the linear part of the curve of growth, this corresponds to a rest equivalent width of $74 \pm 34$ mÅ, or $\log N_{\text{HI}} = 13.2 \pm 0.2$ cm$^{-2}$. Danforth et al. (2015) find a bivariate distribution of H\textsc{i} absorbers with $d^2N/\log N/\log d$ with $N = 110 \pm 6$ at this column density. Multiplying by a column density bin width equal to the full range of the measurement uncertainty (0.4 dex), gives $dN/\log d = 44 \pm 2$, the frequency of H\textsc{i} absorbers per unit redshift with a column density $\log N = 13.2 \pm 0.2$. The 1560.9 Å line is at the right wavelength to be C\textsc{iv} associated with MGG -01-04-005, but we do not know the precise velocity of the H\textsc{i} absorption in this particular sight line (see Figure 2). Instead, we estimate the velocity range over which it might be expected using the Ly\alpha and C\textsc{iv} absorption from the other two sight lines: $cz = 1860 \pm 50$ km s$^{-1}$. A full width of 100 km s$^{-1}$
Table 2
Absorption Table

| Target | Species | $\lambda_0$ (Å) | $\lambda_{abs}$ (Å) | $e^c$ (km s$^{-1}$) | $b$ (mÅ) | $\log N^c$ (cm$^{-2}$) | $\sigma$ |
|--------|---------|----------------|---------------------|---------------------|---------|-------------------------|--------|
| J0107A$^b$ | Ly$\alpha$ | 1215.67 | 1223.09 | 1830 ± 10 | 39 ± 9 | 213 ± 117 | 13.74 ± 0.09 | 19.0 |
| ... | Ly$\alpha$ | 1215.67 | 1223.33 | 1888 ± 10 | 40 ± 5 | 568 ± 80 | 14.75 ± 0.20 | 49.9 |
| ... | C IV | 1548.20 | 1558.12 | 1921 ± 10 | 50 ± 10 | 109 ± 18 | 13.47 ± 0.08 | 8.2 |
| ... | C IV | 1550.77 | 1560.71 | 1921 | 40 | 109 | 13.47 | ... |
| ... | C II | 1334.53 | 1342.96 | 1893 ± 6 | 12 ± 10 | 33 ± 21 | 13.28 ± 0.22 | 6.6 |
| ... | Si II | 1260.42 | 1268.36 | ... | 20 | <25 | <12.2 | <3 |
| ... | Si IV | 1402.77 | 1411.61 | ... | 20 | <22 | <12.7 | <3 |
| J0107B$^c$ | Ly$\alpha$ | 1215.67 | 1223.12 | 1836 ± 75 | 4 ± 10 | 34 | 13.16 | 6.2 |
| ... | Ly$\alpha$ | 1215.67 | 1223.41 | 1908 ± 10 | 17 ± 12 | 354 | 15.84 | 45.0 |
| ... | C IV | 1548.20 | ... | ... | ... | <57 | <13.43 | <3 |
| ... | C IV | 1548.77 | ... | ... | ... | <57 | <13.45 | <3 |
| ... | Si II | 1334.53 | 1343.17 | 1939 ± 15 | 27 ± 23 | 24 ± 22 | 13.10 ± 0.24 | ~3 |
| ... | Si IV | 1260.42 | 1268.36 | ... | 20 | <23 | <12.2 | <3 |
| ... | Si IV | 1402.77 | 1411.62 | 1891 ± 10 | 21 ± 10 | 36 ± 22 | 12.95 ± 0.20 | 3.2 |
| J0107C$^d$ | C IV | 1548.20 | 1557.97 | 1893 ± 7 | 34 ± 11 | 96 ± 44 | 13.43 ± 0.15 | 8.8 |
| ... | C IV | 1550.77 | ... | 1893 | 34 | 96 | 13.43 | ... |

Notes.

$^a$ The errors on $\log N$ represent formal fitting errors from $\chi^2$ minimization. We have reason to believe the errors on $\log N_{HI}$ are actually much larger, as discussed in Section 4.

$^b$ The weak line of the C IV doublet is assumed to be blended with an unknown weak line, as Voigt fitting results in a column density that is too high given known line ratios for C IV. We adopt the strong doublet line values for the 1550 Å line as a reasonable proxy.

$^c$ Since the C IV values for this sight line are upper limits, the observed wavelengths are based on the host galaxy redshift and assumed to be 1558.07 Å and 1560.50 Å. These have been used as the profile centers in Figure 2.

$^d$ The weak line of the C IV doublet is highly blended with unidentified lines and thus no measurement was made, so we follow the same procedure as in footnote b.

corresponds to $\Delta z = 3.3 \times 10^{-4}$. Multiplying this $\Delta z$ by the Ly$\alpha$ absorber frequency at that column density and redshift, the probability for finding an unrelated Ly$\alpha$ line by chance at the location of the expected C IV line is $\sim 1.5\%$. This probability scales linearly with the redshift width $\Delta z$ of the allowed line centroid.

In summary, the Ly$\alpha$ and C IV absorption lines in these three sight lines are over-plotted in Figure 3. The Ly$\alpha$ lines in J0107A and J0107B share both velocity components although the lower velocity component is quite weak in J0107B. J0107A and J0107C have C IV absorption that aligns with the higher velocity component and with each other. The velocity and velocity width coincidences between these two features argue in favor of the hypothesis that the J0107C feature is also C IV. While the C IV 1548 Å identifications are confirmed by the presence of weak 1550 Å absorption in J0107A and B, the C IV 1548 Å identification in J0107C could instead be an intervening Ly$\alpha$ absorber at a different redshift. Therefore, the higher velocity component is shared by at least two and maybe all three sight lines. The lower velocity component is present in J0107B without doubt and probably present, although weakly, in J0107B. While there is no evidence for the lower redshift component in J0107C, we cannot rule out its presence since we have only C IV coverage in that sight line and the lower redshift component appears to be metal-free at the sensitivity level of the COS spectroscopy in hand.

3. FOREGROUND GALAXY: MCG-01-04-005

The galaxy MCG-01-04-005 lies to the WNW of the LBQS triplet and is projected 8'8 (68 kpc) on the sky from J0107A, 9'1 (71 kpc) from J0107B, and 8'3 (64 kpc) from J0107C (see Figure 1). Its H I 21 cm centroid velocity (1865 ± 6 km s$^{-1}$; Meyer et al. 2004) is in between the two velocity components detected in FUV absorption (see Section 2.1) and it has a B-band luminosity of $\sim 0.07 L^*$ (Doyle et al. 2005).

3.1. Galaxy Imaging and Star Formation Rate (SFR)

H$\alpha$ and R-band images of MCG-01-04-005 were obtained in 2013 November using the SPIcam imager on the Apache Point Observatory 3.5 m telescope (APO). Six 300 s exposures in the R-band and six 900 s exposures in H$\alpha$ (R: 6492 Å, $\Delta \lambda = 1544$ Å; H$\alpha$: 6570 Å, $\Delta \lambda = 75$ Å) were acquired under $\sim 1''$ seeing conditions. The narrowband filter covers an area smaller than the detector field of view (FOV), yielding an unvignetted FOV of $\sim 3.5 \times 3.5$, from which the subimage in
Figure 4 is extracted. A standard photometric procedure of subtracting a scaled R-band image from the Hα image was used to isolate Hα emission. In the pure emission-line image, counts from a $42'' \times 62''$ (150 $\times$ 220 pixel, see Figure 4) rectangular area bounding the estimated extent of the galaxy emission were measured. An equal-sized rectangular sky region from the same image was subtracted. Assuming appropriate background subtraction and Poissonian error statistics, the resulting galaxy Hα count rate was $54 \pm 1$ cts $s^{-1}$. However, our Hα count rate is contaminated by [N II] emission that closely flanks Hα and thus falls within the filter bandwidth. To remove this, optical spectra of MCG-01-04-005 were obtained on the same night with the Dual Imaging Spectrograph (DIS) at APO. The two [N II] emission features flanking the Hα emission peak were measured and the ratio of emission was found to be $F$(N II)/$F$ (Hα) = 0.31. Therefore, our corrected pure Hα count rate is $37 \pm 1$ cts $s^{-1}$.

Using the standard star BD+28 4211 to flux calibrate, an observed Hα flux of $(2.09 \pm 0.06) \times 10^{-14}$ erg $s^{-1}$ cm$^{-2}$ was measured for the galaxy. Galactic foreground extinction was determined using the extinction law of Fitzpatrick (1999), assuming $R_V = 3.1$ and $E(B - V) = 0.043 \pm 0.006$ mag (Schaffen & Finkbeiner 2011), yielding an extinction-corrected Hα flux of $(2.29 \pm 0.07) \times 10^{-14}$ erg $s^{-1}$ cm$^{-2}$; no extinction intrinsic to MCG-01-04-005 was assumed. We use a luminosity distance of $\sim 27$ Mpc (Bennet et al. 2013; also consistent with Tully et al. 2008 distance measurements to an equivalently redshifted galaxy group). This corresponds to a luminosity of $L_{H\alpha} = (1.99 \pm 0.06) \times 10^{39}$ erg $s^{-1}$. Using the calibration of Hunter et al. (2010), we obtain a current SFR of $\approx 0.01$ $M_\odot$ yr$^{-1}$.

We can also infer a galaxy’s recent SFR from its FUV luminosity. MCG-01-04-005 was observed by the GALEX in both the FUV and NUV imaging bands as part of its All Sky Imaging Survey. These shallow (108 s) exposures found a GALEX FUV magnitude of $17.31 \pm 0.08$ for MCG-01-04-005 (we have incorporated the absolute photometric uncertainty of GALEX into this magnitude uncertainty; Morrissey et al. 2007), which corresponds to an extinction-corrected luminosity of $L_{FUV} = (5.1 \pm 0.4) \times 10^{-26}$ erg $s^{-1}$ Hz$^{-1}$ using the procedure outlined above. This luminosity implies that the galaxy’s SFR is $\approx 0.06$ $M_\odot$ yr$^{-1}$ (Hunter et al. 2010), $\sim 6$ times higher than the Hα-derived value.

The higher SFR derived from the GALEX FUV luminosity is not surprising since Hα measures star formation over the past 10 Myr, whereas FUV luminosity measures star formation in the past 10-100 Myr (Hunter et al. 2010). Nevertheless, as evidenced by its low Hα- and FUV-inferred SFRs, MCG-01-04-005 is not currently a starburst galaxy nor has it been one in the recent past. All indications are that it is a rather normal $L \sim 0.1 L^*$ galaxy.

4. SIZE OF A TYPICAL PHOTOIONIZED HALO CLOUD

These three sight lines present the opportunity to obtain limits on the physical extent of two typical late-type galaxy halo clouds. From the aspect of its SFR, MCG-01-04-005 appears to be entirely normal, certainly not a starburst, over the recent past. The impact parameter for these sight lines is a modest number of disk radii and only $0.4-0.5 R_{vir}$ (based on a halo-matching formalism; Stocke et al. 2013). This is comparable to or less than the $0.5-1 R_{vir}$ region for which very high covering factors in Lyα and/or O VI are found around late-type galaxies (Tumlinson et al. 2011; Stocke et al. 2013; Bordoloi et al. 2014). Therefore, this situation appears entirely typical for the study of photoionized halo clouds around late-type galaxies.

There are two velocity components to the Lyα absorption, which are present in two sight lines: J0107A and J0107B, separated by 10 kpc at the distance of MCG-01-04-005. This match sets firm lower limits on the transverse sizes on the sky of these two clouds. While Lyα is quite strong in both sight lines for the $\sim 1900$ km s$^{-1}$ absorber, the lower velocity ($\sim 1830$ km s$^{-1}$) Lyα absorption in J0107B is so much weaker than in J0107A that the lower velocity cloud may be only slightly $>10$ kpc in extent on the sky. These firm lower limits are already larger than most of the CGM cloud sizes inferred by Stocke et al. (2013) and near the median value for the sizes inferred by Werk et al. (2014). Assuming a typical CGM cloud total hydrogen density of $n_H = 10^{-15}$ cm$^{-3}$ for a spherical CGM cloud yields a lower limit on the mass of these two clouds: $\geq 4.5 \times 10^6 M_\odot$. However, additional information is available that bears on the sizes and masses of these clouds.

For the J0107C sight line, the absorption due to these clouds is ambiguous due to the presence of an LLS at higher redshift, which obscures the portion of the UV spectrum that contains Lyα associated with MCG-01-04-005. However, in this case, there is a shallow absorption present at just the right velocity to be C IV 1548 Å in the $\sim 1900$ km s$^{-1}$ absorber. Additionally, this feature has a similar line width to the C IV found in the J0107A sight line (see Figure 3), so that C IV is a very plausible identification for this feature. However, we cannot rule out entirely that this absorption line could be Lyα at a higher redshift, though the probability of such a chance coincidence is small ($\leq 2\%$). Additionally, there is a marginal detection of C IV 1550 Å in J01017C which falls between two strong, intervening Lyα absorbers. Therefore, only slightly more speculatively, we conclude that the higher velocity ($\sim 1900$ km s$^{-1}$) cloud...
extends $>23$ kpc on the sky. While we can use this limit as the minimum cloud extent in one-dimension (approximately tangential to the impact parameter vector; see Figure 1), we do not know the other dimensions explicitly. A plausible lower size limit for the other dimension on the plane of the sky can be set at $\geq 5$ kpc using the distance from the J0107B sight line to the cord connecting sight lines A and C (since our observations suggest a continuous absorption between sight lines A and C; see Figure 1). Assuming an ellipsoidal cloud with axes of 5 kpc $\times$ 5 kpc $\times$ 23 kpc finds a minimum mass of $\geq 5 \times 10^6 M_\odot$. Assuming $\geq 23$ kpc for all three dimensions of this cloud results in nearly a $10^8 M_\odot$ lower limit.

### 4.1. Uncertainties in H I Column Density

In Section 4.2, we will use CLOUDY (Ferland et al. 1998) photoionization models to attempt to constrain the line-of-sight thickness of the $\sim 1900$ km s$^{-1}$ absorber in J0107A. CLOUDY outputs rely on accurate absorption-line measurements, but the $N_{\text{HI}}$, value from our Voigt profile fits requires re-evaluation as the Ly$\alpha$ profile is slightly saturated in both velocity components and spectroscopy of the higher-order Lyman lines is not available in this case. The values listed in Table 2 for the Ly$\alpha$ line are the values that minimize the $\chi^2$ of the Voigt-profile fit, but since we are on the flat part of the curve of growth there is a very large uncertainty in column density and $b$-value for a given equivalent width.

Thus, we will treat the H I column density listed in Table 2 for the $\sim 1900$ km s$^{-1}$ absorber as untrustworthy and estimate its value indirectly. This is unfortunate but unavoidable when the only H I line that can be fit is a saturated Ly$\alpha$ profile with no damping wings. A famous precedent from the literature may help illustrate this point. Weymann et al. (1995) observed 3C 273 with HST/GHRS using the G160M grating and found a best-fit Voigt profile with log $N_{\text{HI}}=14.22 \pm 0.07$ and $b=34 \pm 3$ km s$^{-1}$ for the $\sim 1585$ km s$^{-1}$ Ly$\alpha$ absorber associated with the Virgo cluster. We note that the S/N and spectral resolution of this HST/GHRS spectrum of 3C 273 are comparable to those of the HST/COS spectrum of J0107A and the best-fit parameters from the Ly$\alpha$ line fits are comparable as well. Later, Far-ultraviolet Spectroscopic Explorer (FUSE) data became available for 3C 273 and absorption from Ly$\beta$-Ly$\gamma$ were found at the same redshift (Sembach et al. 2003). When a curve-of-growth was generated from these higher-order Lyman lines Sembach et al. (2003) found log $N_{\text{HI}}=15.85^{+0.10}_{-0.08}$ and $b=16 \pm 1$ km s$^{-1}$. The $b$-value was reduced by a factor of two compared to the initial Weymann et al. (1995) value and the column density increased by a factor of more than 40! Sembach et al. (2003) attributed the discrepancy partially to very low column density component structure that affects the Ly$\alpha$ profile but is undetectable in the higher-order Lyman series lines. Therefore, we must treat an $N_{\text{HI}}$ value obtained from Ly$\alpha$ profile fitting alone as uncertain, very likely a lower limit, unless other physical constraints can be identified.

Since $N_{\text{HI}}$ is underconstrained by the COS data alone, we have imposed the condition that the J0107A absorber metallicity should be consistent with the galaxy metallicity. This is reasonable because there are no other bright galaxies close to MCG-01-04-005; the nearest brighter galaxy is NGC 448, a 0.6 L$^*$ S0 galaxy $\sim 750$ kpc away on the sky. This distance on the sky is nearly five times the virial radius for NGC 448 and close to the maximum distance that metals have been detected from any bright galaxy in the current epoch (Stocke et al. 2006, 2013). We conclude that any metals present in these absorbers have originated in MGC-04-01-005. If gas expelled by MCG-04-01-005 mixed with IGM gas it could have an even lower metallicity and an even higher $N_{\text{HI}}$. However, such extreme values do not give Ly$\alpha$ profile fits consistent with the COS spectrum of J0107A nor do they satisfy the photoionization modeling requirements presented below.

We have measured a metallicity for MCG-01-04-005 of $[O/H] = -0.15 \pm 0.19$ (i.e., $Z_{\text{gal}} \sim 0.7 Z_\odot$) using our APO/DIS long-slit spectrum (see Section 3.1) with the N2 index calibration of Pettini & Pagel (2004) and the solar oxygen abundance of Asplund et al. (2009). For the absorber metallicity to be consistent with the galaxy metallicity, log$(Z_{\text{abs}}/Z_\odot) = -0.53$ to 0.23 (i.e., within $2\sigma$ of the galaxy’s nominal value of $[O/H] = -0.15$, or the 95% confidence band). To satisfy this constraint, the H I column density of the $\sim 1900$ km s$^{-1}$ absorber in J0107A must lie in the range log $N_{\text{HI}} \approx 15.5 \pm 0.5$. In the photoionization models that follow, this range of values can reproduce all of the observed metal-line columns and limits; i.e., for lower H I columns the C II detection implies a metallicity that is too high and for higher H I columns the Si II and Si IV upper limits imply a metallicity that is below this range.

### 4.2. Photoionization Modeling

In this sub-section, we use CLOUDY photoionization modeling both to obtain additional size constraints for the $\sim 1900$ km s$^{-1}$ absorber in J0107A and also to show that such size constraints are quite uncertain using the minimal data in-hand: $N_{\text{HI}}, N_{\text{C II}}, N_{\text{C IV}},$ and limits on the column densities of Si II and Si IV (see Table 2). We use a plane-parallel CLOUDY model irradiated by the extragalactic ionizing field as specified by Haardt & Madau (2012) to search for a single-phase solution that self-consistently reproduces the measured column densities and limits. We assume that all species are solely photoionized and examine the temperature, $T$, hydrogen density, $n_H$, neutral fraction, $f_{\text{HI}}$, and line-of-sight thickness, $t$, of the modeled cloud as a function of ionization parameter, $U = n_e/n_{\text{HII}}$, and metallicity, $Z$.

Since the H I column density derived from our Voigt profile fits to Ly$\alpha$ is very uncertain, we use the CLOUDY models to constrain $N_{\text{HI}}$ using the measured column densities of C II and C IV, and the upper limits on the Si II and Si IV columns, as discussed in Section 4.1. Our primary interest is in the range of allowable ionization parameters that these data support, and the line-of-sight thicknesses that can be derived from these values, not the absorber metallicity, which we use only to constrain $N_{\text{HI}}$.

The CLOUDY models associated with this revised column density for the $\sim 1900$ km s$^{-1}$ component in J0107A (log $N_{\text{HI}}=15.5 \pm 0.5$) are shown in Figure 5(a). The metallicity of MCG-01-04-005 is shown as a solid horizontal line with a light gray band indicating its $2\sigma$ uncertainty. The curved solid lines indicate the region of parameter space consistent with the measured C II and C IV column densities, with the flanking dashed lines showing the $1\sigma$ uncertainties in the measured columns modulo the very large uncertainty in the H I column. The dot-dashed lines show the upper limits on the Si II and Si IV columns with the tick marks pointing toward the allowable region of parameter space. The filled gray area shows the
region of parameter space that is consistent with all of the constraints and the star indicates the fiducial solution where the measured C II and C IV columns agree exactly.

From this model, we estimate that log \( U = -2.6_{-0.4}^{+0.4} \) for this absorber; the large uncertainty reflects the large uncertainty in \( N_{\text{HI}} \). At the fiducial solution, we find \( T \approx 11,000 \) K, \( n_{\text{HI}} \approx 3 \times 10^{-4} \) cm\(^{-3}\), \( f_{\text{HI}} \approx 0.3\% \), and \( t \approx 1 \) kpc. The range of line-of-sight thicknesses allowed by our CLOUDY model is shown in Figure 5(b), which displays the same shaded region and metallicity indicators as Figure 5(a) with contours of constant cloud thickness overlaid. From this plot, we conclude that the indicative cloud thickness is \( \approx 0.5-5 \) kpc.

Guided by the fiducial cloud thickness (1 kpc) and cloud density (\( 3 \times 10^{-4} \) cm\(^{-3}\)) from the CLOUDY models and the cloud size limit (>10 kpc) on the sky from the common absorbers, a constant density ellipsoidal cloud with minimum sizes of 1 and 10 kpc in two of the three-dimensions is suggested. Assuming 10 kpc for the third cloud dimension (second transverse dimension on the sky) finds a rough cloud mass limit of \( \geq 3 \times 10^5 M_\odot \). Allowing lower density and larger volume models as in Figure 5 does not change this limit appreciably. However, if we presumed C IV identification for the absorption line detected in Q0107C is correct, the lower mass limit inferred for this spheroidal model is a factor of four larger.

In summary, for all cases described in this section, most lower limits on cloud mass are in the range of \( 0.3-5 \times 10^6 M_\odot \). If we had to rely on photoionization modeling alone, then the inferred mass would be about 100 times less than this lower limit by assuming that each cloud dimension is \( \sim 1 \) kpc. Clearly, the physical limits derived from multiple sight lines are extremely valuable in estimating CGM cloud parameters.

While these values make various assumptions to arrive at a lower mass limit, each of these limiting values for CGM cloud masses are better constrained than those found in either Stocke et al. (2013) or Werk et al. (2014) based solely on simple CLOUDY photoionization modeling. However, the current result supports the contention made by those authors that at least some CGM clouds have very large sizes and masses. Furthermore, while we cannot, on the basis of current data, entirely rule out the contention of Werk et al. (2014) that the photoionized phase is a monolithic structure around each late-type galaxy, the limited size on the sky of \( \sim 10 \) kpc for the lower velocity absorber argues weakly against that model.

5. CONCLUSIONS

Using three neighboring QSO sight lines called the LBQS Triplet, we have determined that two photoionized CGM gas clouds in the halo of the \( \sim 0.1 L^* \) late-type galaxy MCG-01-04-005 have physical extents on the sky of \( \geq 10 \) kpc and total masses \( \geq 3 \times 10^5 M_\odot \). Most size constraints available using common absorptions in the COS FUV spectra of the LBQS Triplet require minimum masses of \( \sim 10^6 M_\odot \). Given that MCG-01-04-005 is a typical, non-starburst low-luminosity galaxy, and that the impact parameters for these absorbers are typical for CGM absorbers at \( 0.4-0.5 R_{\text{vir}} \), we argue that these results are also typical for photoionized CGM clouds in general. Therefore, these results support inferences by Tumlinson et al. (2011), Stocke et al. (2013), Werk et al. (2014), and others that individual CGM clouds can be very massive and the ensemble of such clouds contains a significant baryon reservoir, comparable to the mass in a galaxy’s stars or larger! The following results led us to these conclusions and represent the main observational findings of this paper.

1. The absorption line data from the HST/COS FUV spectra of the LBQS Triplet (J0107A,B,C) finds common absorption at \( z = 0.0063 \) in two velocity components (\( \sim 1830 \) and 1900 km s\(^{-1}\)) as follows: Ly\( \alpha \) in J0107A,B; C IV in J0107A,C; C II in J0107A,B; and upper limits for C IV in J0107B, Si II and Si IV in J0107A,B. The common Ly\( \alpha \) and C IV absorptions support minimum cloud sizes for both velocity components of \( \geq 10 \) kpc. A more speculative detection of C IV 1548 Å in J0107C suggests an even larger size limit of \( \geq 23 \) kpc. The measured values for the absorption line detections can be found in Table 2.

2. Using ground-based Hα and space-based GALEX imaging, we find that the SFR in MCG-01-04-005 is small (between \( \sim 0.01-0.06 M_\odot \) yr\(^{-1}\)) in the last 100 million years. We conclude that the galaxy is a normal, low luminosity late-type galaxy that has not had a significant starburst in the last 10\(^8\) years at least.

3. Using C II and C IV detections and limits on Si II and Si IV at \( \sim 1900 \) km s\(^{-1}\) in J0107A, single-phase photoionization
models have been constructed imposing $Z_{\text{abs}} \sim Z_{\text{gal}}$ to limit the range of acceptable H\textsc{i} columns (Section 4). These CLOUDY models find $U = -2.6^{+0.2}_{-0.2}$ for this absorber and derived physical quantities of $n_{\text{H}} \sim 3 \times 10^{-4}$ cm$^{-3}$, $f_{\text{H}} \sim 0.3\%$, and $t \sim 1$ kpc. While this thickness ($t$) is smaller than the minimum size on the sky obtained from the common absorptions, the range of cloud thicknesses allowed by the CLOUDY models is consistent with an ellipsoidal cloud. However, these models are quite uncertain providing only indicative results on cloud thickness. The common absorptions in the three sight lines provide much better constraints requiring large cloud sizes and masses.

4. Since the common absorptions provide only firm lower limits on transverse cloud sizes, these observations cannot rule out the presence of a monolithic photoionized phase gas around this galaxy. However, the absence of C\textsc{iv} absorption at $\sim 1830$ km s$^{-1}$ in J0107C and the weakness of the Ly$\alpha$ absorption at this velocity in J0107B argue weakly against that model (Werk et al. 2014) by suggesting a cloud size not much larger than 10 kpc for that absorber.

Simon Morris and Neil Creighton are thanked for obtaining the excellent HST/COS spectra used for this investigation. We thank the Apache Point Observatory (APO) for making available 3.5 m observing time to obtain images and long-slit spectra of MGC-01-04-005. The authors thank the National Science Foundation for support of this research at the University of Colorado through grant AST 1109117.

Facilities: HST (COS), GALEX, ARC

REFERENCES

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Bennet, C. L., Larson, D., Weiland, J. L., et al. 2013, ApJS, 208, 20
Bordoloi, R., Tumlinson, J. T., Werk, J. K., et al. 2014, ApJ, 796, 136
Borthakur, S., Heckman, T., Strickland, D., et al. 2013, ApJ, 768, 18
Bowen, D. V., Tolstoy, E., Ferrara, A., Blades, J. C., & Brinks, E. 1997, ApJ, 478, 530
Chen, H.-W., Lanzetta, K. M., & Webb, J. K. 2001, ApJ, 556, 158

Crichton, N. H. M., Morris, S. L., Bechtold, J., et al. 2010, MNRAS, 402, 1273
Danforth, C. W., Keeney, B. A., Stocke, J. T., Shull, J. M., & Yao, Y. 2010, ApJ, 720, 976
Danforth, C. W., Tilton, E. M., Shull, J. M., et al. 2014, arXiv:1402.2655
Danforth, C. W., Tilton, E. M., Shull, J. M., et al. 2015, ApJ, submitted (arXiv:1402.2655)

Doyle, M. T., Drinkwater, M. J., Rohde, D. J., et al. 2005, MNRAS, 361, 34
Ferland, G. J., Korista, K. T., Verner, D. A., et al. 1998, PASP, 110, 761
Fitzpatrick, E. L. 1999, PASP, 111, 63
Foltz, C. B., Chaffee, F. H., Hewett, P. C., et al. 1987, AJ, 94, 1423
Green, J. C., Froning, C. S., Osterman, S., et al. 2012, ApJ, 744, 60
Haardt, F., & Madau, P. 2012, ApJ, 746, 125
Hunter, D. A., Elmegreen, B. G., & Ludka, B. C. 2010, AJ, 139, 447
Koribalski, B. S., Staveley-Smith, L., Kilborn, S. D., et al. 2004, AJ, 128, 16
Lehner, N., Howk, J. C., & Wakker, B. P. 2015, ApJ, 804, 79
Meyer, M. J., Zwaan, M. A., Webster, R. L., et al. 2004, MNRAS, 350, 1195
Morris, S. L., Weymann, R. J., Dressler, A., et al. 1993, ApJ, 419, 524
Morrissey, P., Conrow, T., Barlow, T. A., et al. 2007, ApJS, 173, 682
Mulchaey, J. S. 2000, ARA&A, 38, 289
Mulchaey, J. S., Mushotzky, R. F., Burstein, D., & Davis, D. S. 1996, ApJL, 456, L5
Muzahid, S. 2014, ApJ, 784, 5
Penton, S. V., Stocke, J. T., & Shull, J. M. 2002, ApJ, 565, 720
Penton, S. V., Stocke, J. T., & Shull, J. M. 2004, ApJS, 152, 29
Pettini, M., & Pagel, B. E. J. 2004, MNRAS, 348, L59
Prochaska, J. S., Weiner, B., Chan, H.-W., Cooksey, K., & Mulchaey, J. 2011, ApJS, 193, 28
Savage, B. D., Kim, T.-S., Wakker, B. P., et al. 2014, ApJS, 212, 8
Schaffey, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Sembach, K. R., Howk, J. C., Savage, B. D., Shull, J. M., & Oegerle, W. R. 2003, ApJ, 561, 573
Shull, J. M. 2014, ApJ, 784, 142
Shull, J. M., Maloney, J., Danforth, C. D., & Tilton, E. M. 2015, ApJ, in press (arXiv:1502.00637)
Stocke, J. T., Keeney, B. A., Danforth, C. W., et al. 2013, ApJ, 763, 148
Stocke, J. T., Keeney, B. A., Danforth, C. W., et al. 2014, ApJ, 791, 128
Stocke, J. T., Penton, S. V., Danforth, C. W., et al. 2006, ApJ, 641, 217
Thom, C., Tumlinson, J., Werk, J. K., et al. 2012, ApJL, 758, L41
Tripp, T. M., Lu, L., & Savage, B. D. 1998, ApJ, 508, 200
Tully, R. B., Shaya, E. J., Karachentsev, I. D., et al. 2008, ApJ, 676, 184
Tumlinson, J., Thom, C., Werk, J. K., et al. 2011, Sci, 334, 948
Tumlinson, J., Thom, C., Werk, J. K., et al. 2013, ApJ, 777, 59
Werk, J., Prochaska, J. X., Thom, C., et al. 2013, ApJ, 704, 17
Werk, J., Prochaska, J. X., Tumlinson, J. T., et al. 2014, ApJ, 792, 8
Weymann, R., Rauch, M., Williams, R., Morris, S., & Heap, S. 1995, ApJ, 438, 650