An HST/COS legacy survey of intervening Si III absorption in the extended gaseous halos of low-redshift galaxies^{★,★★}

P. Richter^{1,2}, B. P. Wakker³, C. Fechner¹, P. Herenz¹, T. Tepper-García⁴, and A. J. Fox⁵

¹ Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Str. 24/25, 14476 Golm, Germany
 e-mail: prichter@astro.physik.uni-potsdam.de

² Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany

³ Department of Astronomy, University of Wisconsin-Madison, 475 North Charter Street, Madison, WI 53706, USA

⁴ Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia

⁵ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

Received 22 July 2015 / Accepted 10 March 2016

ABSTRACT

Aims. Doubly ionized silicon (Si III) is a powerful tracer of diffuse ionized gas inside and outside of galaxies. It can be observed in the local Universe in ultraviolet (UV) absorption against bright extragalactic background sources. We here present an extensive study of intervening Si III-selected absorbers and study the properties of the warm circumgalactic medium (CGM) around low-redshift ($z \leq 0.1$) galaxies.

Methods. We analyzed the UV absorption spectra of 303 extragalactic background sources, as obtained with the Cosmic Origins Spectrograph (COS) on-board the *Hubble* Space Telescope (HST). We developed a geometrical model for the absorption-cross section of the CGM around the local galaxy population and compared the observed Si III absorption statistics with predictions provided by the model. We also compared redshifts and positions of the absorbers with those of $\sim 64\,000$ galaxies using archival galaxy-survey data to investigate the relation between intervening Si III absorbers and the CGM.

Results. Along a total redshift path of $\Delta z \approx 24$, we identify 69 intervening Si III systems that all show associated absorption from other low and high ions (e.g., H I, Si II, Si IV, C II, C IV). We derive a bias-corrected number density of $dN/dz(\text{Si III}) = 2.5 \pm 0.4$ for absorbers with column densities $\log N(\text{Si III}) > 12.2$, which is ~ 3 times the number density of strong Mg II systems at $z = 0$. This number density matches the expected cross section of a Si III absorbing CGM around the local galaxy population with a mean covering fraction of $\langle f_c \rangle = 0.69$. For the majority (~ 60 percent) of the absorbers, we identify possible host galaxies within 300 km s^{-1} of the absorbers and derive impact parameters $\rho < 200 \text{ kpc}$, demonstrating that the spatial distributions of Si III absorbers and galaxies are highly correlated.

Conclusions. Our study indicates that the majority of Si III-selected absorbers in our sample trace the CGM of nearby galaxies within their virial radii at a typical covering fraction of ~ 70 percent. We estimate that diffuse gas in the CGM around galaxies, as traced by Si III, contains substantially more (more than twice as much) baryonic mass than their neutral interstellar medium.

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

1. Introduction

Galaxies at low and high redshift are surrounded by massive gaseous halos. These halos are believed to be built up and fed by large-scale gas circulation processes, such as accretion from the intergalactic medium (IGM), galactic winds, and outflows powered by star formation and active galactic nuclei, as well as minor and major mergers that result from the on-going hierarchical formation and evolution of galaxies. Such gaseous material in extended galaxy halos is nowadays often referred to as the circumgalactic medium (CGM). We here define the CGM as diffuse

neutral and ionized gas that is located within the virial radius of a galaxy, but outside of its (main) stellar body.

Observational and theoretical studies imply that the CGM is a key component in the ongoing process of galaxy formation and evolution. Because the gas-consumption timescales of late-type galaxies are short compared to their lifetimes, they must gain gaseous material from outside (e.g., from the IGM and/or from merger processes) through the CGM to sustain their ongoing star formation. The manner in which the gas makes its way from the IGM/CGM to the disks of late-type spirals is not well understood, however. The classical picture of accretion (e.g., Rees & Ostriker 1977; White & Rees 1978; Birnboim & Dekel 2003) and the “hot-” and “cold-mode” scenarios (Kereš et al. 2005) most likely are oversimplified, because the underlying physics that describe the large-scale flows of multiphase gas from the outer to the inner regions of a dynamically evolving galaxy is highly complicated (e.g., Mo & Miralda-Escudé 1996; Maller & Bullock 2004). Most likely, only state-of-the-art hydrodynamical simulations that cover the necessary physics and that have the necessary spatial resolution potentially provide realistic

* Based on observations obtained with the NASA/ESA *Hubble* Space Telescope, which is operated by the Space Telescope Science Institute (STScI) for the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5D26555.

** Full Tables A.1 and A.2, and the reduced spectra (FITS files) are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/590/A68>

measures for the amount of gas that is reaching the disk of late-type galaxies and for the timescales that it requires to do so (e.g., van de Voort et al. 2011).

Observations that aim at studying the properties of the CGM are thus extremely important to improve our understanding of gas-accretion processes and provide constraints for numerical models. What observations can provide is a characterization of the distribution of the different gas phases in the CGM, the total mass that it contains (under reasonable assumptions), and the connection between the properties of the CGM and the properties of their host galaxies (e.g., morphology, luminosity, star-formation rate, etc.). The gas densities in the CGM are low, however, so that emission measurements of circumgalactic gas (e.g., in the X-ray regime) typically are limited to the very inner halo regions of nearby galaxies using current instruments (Anderson & Bregman 2011; Dai et al. 2012; Bogdán et al. 2013). Fortunately, absorption-line measurements that use background active galactic nuclei (AGNs; throughout the following we use the abbreviation QSO to refer to the various classes of AGNs collectively) can access physical tracers at the relevant densities with extremely high sensitivity. For such absorption-line measurements the ultraviolet (UV) range is particularly important, as it contains a large number of diagnostic transitions from low, intermediate and high ions of heavy elements and the Lyman series of neutral hydrogen. Consequently, UV absorption-line observations with past and present space-based UV spectrographs such as the Far-Ultraviolet Spectroscopic Explorer (FUSE), the Space Telescope Imaging Spectrograph (STIS) and the Cosmic Origins Spectrograph (COS; the latter two instruments installed on the *Hubble* Space Telescope; HST) provide a wealth of information on the physical and chemical properties of the different gas phases in the CGM of the Milky Way and other galaxies (e.g., Wakker et al. 1999, 2001; Sembach et al. 2003; Richter et al. 2001, 2009, 2011; Tripp et al. 2003; Fox et al. 2005, 2010; Collins et al. 2009; Wakker & Savage 2009; Shull et al. 2009; Prochaska et al. 2011; Tumlinson et al. 2011; Lehner et al. 2013; Keeney et al. 2013; Werk et al. 2013; Stocke et al. 2014; Liang & Chen 2014).

In two previous papers, we have studied the amount and distribution of neutral gas (the so-called high-velocity clouds) in the halos of low redshift galaxies via optical absorption spectroscopy and their contribution to the neutral-gas accretion rate in the local Universe (Richter et al. 2011; Richter 2012). We here continue our long-term strategy to study the circumgalactic medium in the local Universe with an absorption-line survey that aims at characterizing the extent and mass of diffuse ionized gas around low-redshift galaxies using archival UV absorption-line data from HST/COS.

This paper is organized as follows. A short discussion on the importance of doubly ionized silicon as a sensitive tracer for circumgalactic gas is presented in Sect. 2. In Sect. 3 we describe the HST/COS data acquisition, the COS data reduction, the spectral analysis method, and the galaxy data origin. In Sect. 4 we discuss the observed absorber properties, such as their incident rate, their redshift distribution, the distribution of equivalent widths and column densities. In Sect. 5 we model the expected absorption cross section of circumgalactic gas using the local galaxy luminosity function. Section 6 deals with the observed absorber-galaxy connection in our data sample. The ionization conditions and the cosmological mass density of the Si III absorbers are considered in Sect. 7. We discuss our results in Sect. 8 and provide a summary of our study in Sect. 9.

2. On the importance of Si III as a tracer of circumgalactic gas

A particularly powerful transition in the UV to detect ionized interstellar, circumgalactic, and intergalactic gas in a wide range of physical conditions is that of doubly ionized silicon (Si III) at 1206.500 Å (hereafter referred to as Si III λ 1206). This is because of the very high oscillator strength of Si III λ 1206 of $f = 1.63$ (Morton 2003) and the relatively large cosmic abundance of silicon ($\log(\text{Si}/\text{H})_{\odot} = -4.49$; Asplund et al. 2009). Doubly ionized silicon is a Mg-like ion with a closed-subshell $3s^2$ valence-electron structure. The ionization-energy boundaries of the Si III ion are 16.35 and 33.49 eV (Morton 2003). As a result, detectable Si III arises from both diffuse photoionized as well as collisionally ionized gas at moderate temperatures ($T < 10^5$ K; see Shull et al. 2009).

To demonstrate the diagnostic power of the Si III λ 1206 transition for the study of the CGM we show in Fig. 1 the expected fractional abundance of the Si ions Si II–Si VIII in gas at $z = 0$ that is exposed to the local UV background. For the UV background we use a modified version of the model by Haardt & Madau (2012), in which we re-scale the photoionization rate to a value of $\log \Gamma = -13.6$ to compensate for the apparent discrepancies between the Haardt & Madau model and recent observational results (see Kollmeier et al. 2014; Wakker et al. 2015; Shull et al. 2015). The calculations (Fechner, in prep.) are based on ionization models performed with the ionization code Cloudy (v13.03; Ferland et al. 2013). As can be seen, doubly ionized Si represents the dominant observable ionization state of Si at densities and temperatures ($\log n_{\text{H}} = -2.0$ to -3.5 , $T < 10^5$ K) that are typical for multiphase circumgalactic gas structures that are embedded in hot coronal gas (see Cen 2013).

In terms of quasar absorption-line systems, Si III λ 1206 absorption in the low-redshift Universe is expected to be detectable (if not blended by other spectral features) in basically *all* damped Lyman α absorbers (DLAs; $\log N(\text{H I}) \geq 20.3$), sub-damped Lyman α absorbers (sub-DLAs; $19.0 \leq \log N(\text{H I}) < 20.3$), Lyman-limit systems (LLS; $17.2 \leq \log N(\text{H I}) < 19.0$), because these are metal-enriched, multiphase absorbers with high gas columns. The majority of Si III-selected absorbers (throughout the following referred to simply as Si III absorbers), however, are expected to arise in ionized metal systems at lower H I column densities ($\log N(\text{H I}) < 17.2$), where the minimum H I column density to detect Si III with HST/COS in solar-metallicity gas at moderate gas densities ($n_{\text{H}} \sim 10^{-3} \text{ cm}^{-3}$) can be as low as $\log N(\text{H I}) = 14$ (see Sect. 7.1).

Low ions with lines in the observable UV, such as O I, C II, and Si II, are only present in mostly neutral or slightly ionized gas (i.e., at high $N(\text{H I})$), while high ions such as C IV and O VI predominantly trace highly-ionized gas at gas densities that are typically below $n_{\text{H}} \sim 10^{-3} \text{ cm}^{-3}$. A Si III-selected absorption-line survey, such as presented in this paper, therefore is expected to be particularly sensitive to detect metal-enriched gas in the inner and outer halos of galaxies and to characterize its spatial distribution and physical properties.

3. Observations, data handling, and analysis method

3.1. COS spectra selection and data reduction

For our study we make use of archival HST/COS data that were retrieved from the HST Science Archive at the Canadian Astronomy Data Centre (CADC). Because we aim at studying

Fig. 1. Ionization fractions of different Si ionization states for different gas densities and temperatures, as calculated from a Cloudy ionization model (including photoionization and collisional ionization) of circumgalactic gas at $z = 0$ using the local UV background. The *upper panel* shows a model for $\log T = 4.2$, the *lower panel* a model for $\log T = 4.4$. The Si III ion represents the dominant ionization state in the density range that is characteristic for circumgalactic gas structures that are embedded in hot coronal gas ($\log n_H = -2.0$ to -3.5).

intervening Si III $\lambda 1206$ absorption in the IGM at $z \leq 0.1$ together with corresponding H I Ly α $\lambda 1215$ absorption we are primarily interested in the wavelength range between 1208 and 1338 Å. This range is covered by the COS G130M grating which operates between $\lambda = 1150$ –1450 Å, providing a spectral resolution of $R \approx 15\,000$ –20 000 (corresponding to an instrumental FWHM of 15–20 km s^{−1}, while the native pixel size is 2 km s^{−1}; Green et al. 2012; Debes et al. 2016). Using the CADCE web interface we searched for all publicly available COS data from all types of extragalactic point sources such as the various types of AGN and galaxies that were observed with the COS G130M grating. By the end of February 2014 we found (and downloaded) G130M data sets for 552 extragalactic sightlines. Whenever G160M data (covering the range $\lambda = 1405$ –1775 Å including the important C IV doublet at 1548.2, 1550.8 Å) were available for these sightlines, we retrieved them as well.

For the further data reduction we used the raw COS spectra of the individual science exposures. The individual exposures were processed with the CALCOS pipeline (v2.17.3) to produce the standard COS x1d fits files. For the coaddition of the individual spectra we then used a custom-written code

that aligns the individual exposures in wavelength space in a fully automated fashion. The code calculates for each exposure a pixel/wavelength calibration based on the line flanks (for spectra with $S/N > 5$) or line centers (for spectra with $S/N \leq 5$) of various interstellar anchor lines that are distributed over the wavelength range of the G130M and G160M spectral ranges. The heliocentric velocity positions of the anchor lines were calibrated for each sightline using H I 21 cm data from the Leiden-Argentine-Bonn (LAB) survey (Kalberla et al. 2005). The individual spectra then were uniformly rebinned and coadded pixel-by-pixel (using the count rate in each pixel), where pixels with known artifacts were flagged accordingly. Errors were calculated in the coadded spectra by weighting by inverse variance. In this way, we obtained for each sightline a calibrated, co-added G130M spectrum (and G160M spectrum, if available). For each sightline we checked the quality of the data reduction by a visual inspection of the final spectrum.

As it turns out, many of the data sets have very low signal-to-noise ratios (S/N) and/or sample background sources with very low redshifts. These spectra are thus not suited to investigating intervening metal absorption at $z \leq 0.1$. We selected only those spectral data that have a minimum S/N per resolution element of four in the wavelength range between 1208 and 1338 Å and for which the redshift of the background source is $z_{\text{QSO}} > 0.03$. This selection reduces the total sample to 303 lines of sight (LOS). In Table A.1 in the Appendix we present a complete list of all 303 QSO sightlines in our COS sample including QSO names and coordinates.

3.2. Redshift-path coverage, absorber identification, and spectral analysis

The next step in our analysis was to characterize the available redshift path to detect intervening Si III+H I Ly α absorption at $z \leq 0.1$ in each spectrum. We generally exclude the velocity range between $|v_{\text{helio}}| = 0$ –500 km s^{−1} where absorption by local disk gas and by intermediate- and high-velocity clouds in the Milky Way halo is found (see, e.g., Wakker & van Woerden 1998; Richter 2006; Shull et al. 2009; Lehner et al. 2012; Putman et al. 2012; Herenz et al. 2013). To sort out regions that may be associated with the background AGN we further ignore the spectral range that lies within 5000 km s^{−1} of z_{QSO} . Finally, we identify and flag along each sightline those spectral regions that are heavily blended by other intervening absorbers (in particular by higher-redshift LLS and DLAs). As a result, we obtain a total absorption redshift path $\Delta z_{\text{abs}} < 0.1$ for each sightline that is available to identify intervening Si III+H I Ly α absorption (see Table A.1, last column).

For the determination of the Si III number density (Sect. 4.2) we further need to consider the detection limit for Si III absorption along each sightline, which depends on the S/N in the relevant part of the spectrum where intervening Si III absorption is expected to occur. The minimum column density, N_{lim} , that can be detected at 3σ significance from an unresolved absorption line with a laboratory wavelength λ_0 and an oscillator strength f in a spectrum with a resolving power R and a given S/N per resolution element is given by (e.g., Richter et al. 2001; Tumlinson et al. 2002):

$$N_{\text{lim}} \approx 1.13 \times 10^{20} \frac{3}{R(S/N)f(\lambda_0/\text{\AA})} \text{ cm}^{-2}. \quad (1)$$

For the only available Si III transition in the UV range we have $\lambda_0 = 1206.500$ Å and $f = 1.62732$ (Morton 2003), so that for a S/N of 4 per resolution element the formal 3σ detection limit

for $R = 15\,000$ is $\log N_{\text{lim}}(\text{Si III}) = 12.46$. More than half of the considered COS spectra have a S/N per resolution element of ≥ 12 , so that for these LOS $\log N_{\text{lim}}(\text{Si III}) \leq 12.0$.

For the identification of intervening Si III absorbers at $z \leq 0.1$ in our COS data sample we used the following strategy. In a first step, we let an automated line-finder algorithm identify absorption features whose wavelengths would correspond to combined Si III/H I Ly α absorption and created a candidate list of possible Si III absorbers. In a second step, we inspected each individual spectrum by eye and created a different (independent) candidate list. For each of the candidates from both lists velocity plots (including all relevant low and high ions in the available wavelength range) were generated and the absorber candidates were analyzed in detail. To meet our selection criteria of a bona fide Si III absorber, we require the significant detection of Si III and H I together with the detection of at least one additional metal ion (C IV, C II, Si IV, Si II) to avoid mis-identifications and false detections due to absorption features of other intervening absorbers at higher redshifts. Si III traces both diffuse ionized gas (as also traced by high ions such as C IV and Si IV) as well as denser, partly neutral gas (as also traced by singly-ionized species such as Si II and Mg II; see Fig. 1), so that the simultaneous detection of Si III with either one of the above listed low and high ions is expected.

We also identified a number of absorber candidates, that possibly show absorption in H I and Si III but lack absorption from any other ion, so that a unambiguous identification cannot be given.

For each intervening Si III absorber we checked for associated absorption in other metal ions (in particular Si II, Si IV, C II, C IV, N V, Fe II). We then measured equivalent widths (and their limits) for the strongest lines of the three different ionization states of silicon (Si II $\lambda 1260$, Si III $\lambda 1206$, Si IV $\lambda 1393$), C II $\lambda 1334$, and C IV $\lambda 1548$, as well as for H I Ly α by a direct pixel integration. Because of the limited spectral resolution and S/N of the COS data and the resulting lack of information about the intrinsic component structure in the absorbers we refrain from performing line fits for the analysis of the metal absorption in the systems. We instead use the apparent-optical depth method (AOD method; Savage & Sembach 1991) to derive column densities for unsaturated absorption in the above-listed lines and lower limits for lines that appear to be saturated. We assume that saturation becomes important for lines that have an absorption depth > 0.3 at the resolution of COS. Only for a small number of absorbers do we use Voigt-profile fitting to estimate the total H I column density from the damping wings of the H I Ly α absorption. The AOD method and Voigt-profile fitting are implemented in the custom-written `span` software package that is based on ESO-MIDAS and its data-reduction libraries (Fontana & Ballester 1995). Laboratory wavelengths and oscillator strengths for all ions were adopted from the compilation by Morton (2003).

3.3. Galaxy data

To statistically investigate the relation between Si III absorbers and low-redshift galaxies we searched for publicly available galaxy data in the SIMBAD data archive¹. Using SIMBAD we generated a list of galaxies with known redshifts located at $z \leq 0.1$ and within 2 deg of each sightline. A redshift of $z = 0.1$ corresponds to a proper distance of 420.9 Mpc at $z = 0.1$ for a standard Λ CDM cosmology with $\Omega_{\Lambda} = 0.72$, $\Omega_{\text{m}} = 0.28$ and

$H_0 = 69.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Hinshaw et al. 2013²). In this way, we obtained redshifts and coordinates for 64 280 galaxies distributed around the 303 COS sightlines. For 40 907 of these galaxies we have additional information on their B -band magnitudes. The distribution of m_B for these systems is shown in Fig. 3. The distribution breaks down at $m_B = 20.0$, with only two percent of the galaxies having $m_B > 20.0$. For $z = 0.1$ and the above given cosmology, $m_B = 20.0$ corresponds to an absolute magnitude of $M_B \approx -18.1$. If we consider the g -band SDSS galaxy-luminosity function (Montero-Dorta & Prada 2009) as reference, this value translates into a lower luminosity cutoff of $L \approx 0.5 L^*$.

For each sightline, we then calculated the projected impact parameters, ρ , of the galaxies to the LOS. There are 11 127 galaxies within $\rho = 1 \text{ Mpc}$ located in the cylindrical volume around the 303 sightlines. This number implies a mean galaxy density of $\phi \approx 0.03 \text{ Mpc}^{-3}$ in our total galaxy sample, which is about seven times the space density of L^* galaxies in the SDSS g -band (Montero-Dorta & Prada 2009).

At this point it is important to mention that the galaxy catalog created in this way is highly inhomogeneous because the data stems from different galaxy surveys and pointed observations. As a result, the individual values for ϕ for each sightline vary considerably. In terms of luminosities, only a few sightlines have galaxy data that are sufficiently deep to detect faint ($L \leq 0.05 L^*$) galaxies. In general, our galaxy data is incomplete for $L < 0.5 L^*$. This aspect needs to be carefully taken into account for the interpretation of the observed absorber/galaxy relation. For many sightlines, we are missing low-luminosity galaxies that may be close to the LOS and/or responsible for the observed metal absorption (see discussion in Sect. 6). We do not consider any other morphological parameters of the selected galaxies (Hubble type, star-formation rate, etc.), because such information is available to us only for a small fraction of the galaxies in our sample.

4. Absorber properties

4.1. Si III detection rate, equivalent widths and column densities

Using the above outlined strategy, we identify 69 intervening Si III absorbers along the 303 selected QSO sightlines. The statistical and physical properties of these 69 intervening absorbers are discussed in this section.

In Table A.2 in the Appendix we list the measured equivalent widths and derived column densities for the various ions detected in these systems. These tables also contain information on two additional strong metal absorbers towards SDSSJ141542.90+163413.8 and UKS-0242-724 that are detected in Si II, Si IV, and other ions, but not in Si III, because there are no useful data in the relevant spectral region where Si III is expected. In Fig. 2 we show five examples for velocity profiles of intervening Si III absorbers with different Si III absorption strengths. The complete set of velocity profiles for all 69 confirmed Si III absorbers is provided in Figs. A.1–A.7 in the Appendix of this paper. Following the criteria defined in the previous section we further identify 20 Si III candidate absorbers along the 303 lines of sight. Although these candidate systems are not considered in the further analysis, we list the QSO names and (possible) absorption redshifts of these systems in Table A.3 in the Appendix.

² These values are consistent at the 2σ level with the latest measured values by the Planck Collaboration (Planck Collaboration XIII 2015).

¹ <http://simbad.u-strasbg.fr>

Fig. 2. Five examples for velocity profiles of Si III-selected absorption line systems in our HST/COS survey with decreasing Si III $\lambda 1206$ absorption strengths (gray-shaded area; *from left to right*). Shown are the velocity profiles of H I, Si III, Si II, Si IV, C II, and C IV (*from top to bottom*) plotted against the absorber's restframe velocity. The names of the background QSOs and the absorption redshifts are indicated above each panel. A complete set of velocity plots for all detected Si III absorbers discussed in this paper is available in the Appendix.

Fig. 3. Distribution of B -band magnitudes for $\sim 41\,000$ galaxies in our sample.

The redshift distribution of the 69 absorbers is shown in Fig. 4, left panel. The absorption redshifts lie between $z = 0.00014$ and $z = 0.09789$. While for $z = 0.01$ – 0.10 the absorbers are uniformly distributed over the surveyed redshift range, the distribution shows a peak in the first redshift bin at $z < 0.01$. This peak is related to an overdensity of Si III absorbers in the broader Virgo-Cluster environment that is traced along several sightlines in our QSO sample. In the middle panel of Fig. 4 we

show the distribution of Si III $\lambda 1206$ equivalent widths of the 69 absorbers. The distribution peaks at relatively low equivalent widths ($W_r \leq 100$ mÅ); 65 percent of the absorbers have $W_r \leq 200$ mÅ, while most of the remaining 35 percent are spread over a large range in W_r between 200 and 700 mÅ. There are two systems that have very large equivalent widths of $W_r > 700$ mÅ, belonging to strong absorption systems towards SDSSJ140732.25+550725.6 and PG 0832+251 (see Appendix).

Si III column densities for the 69 absorbers, as derived from the AOD method (see previous section), are shown in the right panel of Fig. 4. The gray-shaded area (which adds to the green-shaded area) indicates lower limits of $N(\text{Si III})$ for absorbers where the Si III $\lambda 1206$ line shows evidence for saturation. The decline of the observed distribution at low column densities reflects both the inhomogeneous S/N in the spectra as well as the column density distribution that is intrinsic to the absorber population. From the estimate of $N_{\text{lim}}(\text{Si III})$ for each sightline (see Eq. (1)) follows that more than 90 percent of all sightlines are sensitive to detect Si III absorbers with $\log N(\text{Si III}) < 12.2$, but only four such systems are found in our data (fractional abundance $4/69 \approx 0.04$). Therefore, intervening Si III absorbers with $\log N(\text{Si III}) < 12.2$ are rare and may even represent a population that is distinct from the absorbers with higher column densities (as is discussed later). At the high-column density end, the distribution breaks down at $\log N(\text{Si III}) = 14$. Even if some of the saturated absorbers (gray-shaded range) would have logarithmic Si III column densities > 14 , their number would be small compared to absorbers with $\log N(\text{Si III}) < 14$. Our conclusion is that the *characteristic* column density range for intervening Si III absorbers is $\log N(\text{Si III}) = 12.2$ – 14.0 .

Fig. 4. *Left panel:* redshift distribution of the 69 intervening Si III absorbers in our sample. *Middle panel:* distribution of Si III $\lambda 1206$ restframe equivalent widths of the 69 absorbers, obtained from the pixel integration over the Si III velocity profiles. *Right panel:* distribution of logarithmic Si III column densities for the 69 absorbers, derived using the AOD method. The gray-shaded area indicates lower limits for $\log N(\text{Si III})$ for absorbers that have saturated Si III $\lambda 1206$ lines.

4.2. Number density of Si III absorbers

For the determination of the number density of intervening Si III absorbers per unit redshift, dN/dz , we need to consider in detail the completeness of our absorber survey and the selection bias in our QSO sample.

As discussed above, $\log N_{\text{lim}}(\text{Si III}) \geq 12.2$ represents the column density range that is characteristic for intervening Si III absorbers. 63 Si III absorbers in our sample have column densities $\log N_{\text{lim}}(\text{Si III}) \geq 12.2$ and 280 out of the 303 sightlines are sensitive to this level, covering a total redshift path of $\Delta z_{\text{abs}} = 21.95$. The resulting number density thus is $dN/dz = 2.9 \pm 0.4$. The given errors represent statistical errors calculated from Poisson statistics. For $\log N_{\text{lim}}(\text{Si III}) = 11.8$ we derive $dN/dz = 4.0 \pm 0.7$ (31 absorbers, $\Delta z_{\text{abs,tot}} = 7.8$), while for $\log N_{\text{lim}}(\text{Si III}) = 12.6$ the number density is slightly smaller ($dN/dz = 2.1 \pm 0.3$, 49 absorbers, $\Delta z_{\text{abs,tot}} = 23.6$). If we consider only low-column density absorbers with $\log N(\text{Si III}) = 11.8\text{--}12.2$ we obtain $dN/dz \approx 0.3$.

One important effect that influences the observed frequency of intervening absorption systems is the selection bias in the QSO sample that we are using. Most of the bright QSOs in our COS sample have been previously studied using instruments such as HST/STIS, FUSE, and others. While the original motivation to select these background sources certainly was their intrinsic brightness, the re-observation of these sources with COS and the chosen integration time (e.g., the achieved S/N), possibly was motivated by targeting particularly interesting intervening absorbers to perform a detailed study of these systems. Therefore, one of the reasons for limiting the absorber sample to redshifts $z \leq 0.1$ was to avoid the inclusion of targeted observations of stronger intervening metal absorbers at $z > 0.12$ that can be observed in both H I Ly α as well as Ly β .

We have scanned the various original COS proposals that outline the motivation for observing the LOS along which we detect intervening Si III at $z \leq 0.1$. As it turns out, our QSO sample covers most of the sightlines selected for the COS-Dwarfs survey (Bordoloi et al. 2014), a targeted survey of sightlines passing through the virial radius of $z \leq 0.1$ dwarf galaxies to study the CGM of these systems. For an un-biased estimate of $dN/dz(\text{Si III})$ all these sightlines need to be excluded. All in all, we identify 40 QSO sightlines in our sample that have been specifically observed to study circumgalactic gas in the vicinity of known low-redshift galaxies. By removing these sightlines

from our sample we derive the following bias-corrected number densities of Si III absorbers for the different limiting Si III column densities: $dN/dz = 3.8 \pm 0.7$ for $\log N_{\text{lim}}(\text{Si III}) = 11.8$, $dN/dz = 2.5 \pm 0.4$ for $\log N_{\text{lim}}(\text{Si III}) = 12.2$, and $dN/dz = 1.7 \pm 0.3$ for $\log N_{\text{lim}}(\text{Si III}) = 12.6$. For the range $\log N(\text{Si III}) = 11.8\text{--}12.2$ we again obtain $dN/dz \approx 0.3$.

It is evident that these numbers are not substantially different from those derived from the biased sample. This is, however, not surprising because it is known that the UV absorption cross section of the warm CGM around *dwarf galaxies* appears to be small when compared to the warm CGM of more massive galaxies (e.g., Bordoloi et al. 2014; Liang & Chen 2014; see also Sect. 8.3). In other words: only a few additional Si III absorbers are (in a statistical sense) added to our absorber sample when including the pre-selected Bordoloi et al. sightlines, but because of the overall large size of our QSO sample their influence on dN/dz is small.

In Fig. 5 we show the bias-corrected number density of intervening Si III absorbers per unit redshift in our survey, dN/dz , for the three different limiting Si III column densities, $\log N_{\text{lim}}(\text{Si III}) = 11.8, 12.2$ (dashed red line), and 12.6. In the following, we refer to these values when discussing the number densities of intervening Si III absorbers.

4.3. Associated absorption from other ions

4.3.1. H I

As outlined in the introduction, the Si III ion is, because of its ionization potential, a very sensitive tracer for both predominantly neutral as well as predominantly ionized gas in the halos of galaxies. As a consequence, the H I column density in the Si III absorbing gas varies over several orders of magnitudes, ranging from $\log N(\text{H I}) \sim 14$ up to $\log N(\text{H I}) \sim 22$, depending on whether the sight line passes through a galaxy disk or a galaxy halo, and on the local ionization conditions. Detailed ionization models of the Si III absorbers are presented in Sect. 7. In the left panel of Fig. 6 we show the distribution of H I Ly α equivalent widths in the Si III-selected absorbers, which similarly span an extremely large range from $W_r \approx 250 \text{ mÅ}$ to $W_r \approx 5 \text{ Å}$. We generally refrain from estimating the H I column densities from the saturated H I Ly α lines because of the very large uncertainties that such an estimate would be afflicted with.

Fig. 5. Number densities, dN/dz , of intervening Si III absorbers for different limiting column densities.

It is worth noting that our absorber sample contains four damped Ly α /sub-damped Ly α systems (DLAs/sub-DLAs) with $\log N(\text{HI}) > 19.2$, as estimated from fitting the damping wings of the Ly α absorption in these systems. With a total redshift path of $\Delta z_{\text{abs,tot}} = 21.95$, this absorber frequency corresponds to a number density of $dN/dz \approx 0.2$. Despite the low-number statistics, it is worth mentioning this value agrees well with the expected number density of sub-DLAs/DLAs as estimated from the HI mass function of $z \approx 0$ galaxies (Zwaan et al. 2005).

4.3.2. Si II

Detailed ionization models (see Sect. 7) indicate that regions with gas densities $\log n_{\text{H}} \geq -3.5$ and sufficiently large neutral hydrogen column densities are expected to show both Si III as well as Si II absorption. Because Si II and Mg II have almost identical ionization potentials (Morton 2003) and silicon and magnesium have similar solar abundances (Asplund et al. 2009), the absorber statistics for Si II can be directly compared with the well-established statistics on intervening Mg II absorbers. The presence of Si II absorption without associated Si III is basically impossible for any realistic galactic or circumgalactic gas environment (see Sect. 7), so that the fact that our absorber sample is Si III-selected is not expected to introduce a selection bias in our Si II statistics.

Fourty of our Si III absorbers show associated Si II absorption in the strongest of the available Si II lines at $\lambda_0 = 1260.42 \text{ \AA}$. The equivalent-width distribution for Si II $\lambda 1260$ in these absorbers is shown in the middle panel of Fig. 6. It shows that the majority (80 percent) of the detected Si II lines have equivalent widths in the $\lambda 1260$ line of $< 300 \text{ m\AA}$. To compare the observed number density of Si II-bearing absorbers with that of the prominent strong Mg II systems, i.e., systems that have an equivalent width of $W_r \geq 300 \text{ m\AA}$ in the Mg II $\lambda 2976$ line, we need to convert the observed Si II $\lambda 1260$ equivalent widths into Mg II $\lambda 2976$ equivalent widths. For this we use the Si II/Mg II conversion scheme presented in Herenz et al. (2013), after which an equivalent widths of $W_r = 300 \text{ m\AA}$ in the Mg II $\lambda 2976$ line corresponds to an equivalent width of $W_r = 140 \text{ m\AA}$ in Si II $\lambda 1260$, assuming solar relative abundances of Mg and Si. In our absorber sample we have 22 systems that have $W_r \geq 140 \text{ m\AA}$ in the Si II $\lambda 1260$ line, from which we indirectly infer a number density of strong Mg II absorbers at $z \leq 0.1$ of $dN/dz \approx 1.0$. This value is in good

agreement with the expectations for $dN/dz(\text{Mg II } \lambda 2976)$ based on the redshift evolution of strong Mg II absorbers in SDSS data ($dN/dz \sim 0.8$; Nestor et al. 2005; Prochter et al. 2006; Lundgren et al. 2009; Zhu & Menard 2013).

4.3.3. Si IV

There are 38 Si III absorbers in our sample that show associated Si IV absorption (the two available Si IV transitions are located at $\lambda_0 = 1393.8$ and $1402.8 \text{ \AA}$, the former being the stronger of the two transitions; Morton 2003). The distribution of Si IV $\lambda 1393$ equivalent widths of the 38 absorbers detected in Si IV is shown in the right panel of Fig. 6. Similarly as for Si II, the majority of the Si IV $\lambda 1393$ equivalent widths are small (82 percent have $W_r(1393) < 300 \text{ m\AA}$). From the observed frequency of Si IV absorption in the Si III-selected systems we estimate $dN/dz(\text{Si IV}) \geq 1.5$ for $\log N(\text{Si IV}) \geq 12.6$. The occurrence of Si IV absorption without associated Si III absorption in the CGM/IGM is possible, in principle, but is relevant only for absorbers at relatively low gas densities ($\log n_{\text{H}} \leq -4.2$; see Sect. 7). Still, we formally can only give a lower limit for $dN/dz(\text{Si IV})$ from our survey.

4.4. Correlation plots

In Fig. 7 we show correlations between the measured (logarithmic) equivalent widths of Si III $\lambda 1206$, H I Ly α , Si II $\lambda 1260$, and Si IV $\lambda 1393$ for absorbers in which the absorption in these ions is aligned in velocity space within one COS resolution element (20 km s^{-1}). The interpretation of the observed correlations involves the possible presence of different gas phases in the absorbers that may or may not be co-spatial within the overall gas structures.

4.4.1. Si III vs. H I

For $\log [W_r(\text{Ly } \alpha)] \leq 3$ the Si III $\lambda 1206$ equivalent width rises steeply with the mildly increasing equivalent width of the fully saturated H I Ly α absorption (Fig. 7; left panel). This trend indicates (as expected) that Si III and H I trace the same physical regions that span a large range in neutral (and total) gas column densities. For $\log [W_r(\text{Ly } \alpha)] > 3$ the correlation turns over into a somewhat flatter regime because the Si III $\lambda 1206$ absorption itself becomes saturated at such high total gas columns.

4.4.2. Si III vs. Si II

The equivalent widths of Si III $\lambda 1206$ and Si II $\lambda 1260$ clearly are correlated with each other in those absorbers, where both ions are detected (Fig. 7; second panel from left, filled circles). This demonstrates that part of the Si III arises in the same gas phase as Si II, i.e., in predominantly neutral and/or mildly ionized gas. Some of the systems with upper limits in $W_r(\lambda 1260)$ (open circles/arrows) have relatively strong Si III absorption without a Si II counterpart, implying that these absorbers consist of predominantly ionized gas that is traced by higher ions (e.g., Si IV, see below).

4.4.3. Si III vs. Si IV

For systems that show both Si III as well as Si IV absorption the equivalent width of Si III $\lambda 1206$ is also correlated with that of

Fig. 6. Distribution of restframe equivalent widths of H I Ly α (left panel), Si II $\lambda 1260$ (middle panel), and Si IV $\lambda 1393$ (right panel) associated with intervening Si III absorbers.

Fig. 7. Comparison between restframe equivalent widths of Si III, Si II, Si IV, and H I for 69 absorbers. *First panel (left):* Si III $\lambda 1206$ vs. H I Ly α ; *second panel:* Si III $\lambda 1206$ vs. Si II $\lambda 1260$; *third panel:* Si III $\lambda 1206$ vs. Si IV $\lambda 1393$; *fourth panel:* Si II $\lambda 1260$ vs. Si IV $\lambda 1393$.

Si IV $\lambda 1393$, as can be seen in the third panel of Fig. 7 (filled circles). This trend indicates that some part of the Si III resides in a more ionized gas phase that is traced by Si IV (and other high ions such as C IV). The relation is mildly steeper than the one for Si III/Si II, but has as similar level of scatter.

4.4.4. Si II vs. Si IV

In the right panel of Fig. 7 we have plotted the equivalent width of Si II $\lambda 1260$ against that of Si IV $\lambda 1393$ for the absorbers where both ions are detected. The total number of systems that show aligned Si II and Si IV absorption is relatively small (38 percent). This implies that both ions predominantly trace complementary gas phases. For the systems detected in both ions (filled circles) the correlation between $W_r(\text{Si II } \lambda 1260)$ and $W_r(\text{Si IV } \lambda 1393)$ is weak and shows a relatively large scatter.

4.4.5. Interpretation

We conclude that the correlation plots between the equivalent widths of Si III $\lambda 1206$, H I Ly α , Si II $\lambda 1260$, and Si IV $\lambda 1393$ are in line with (and further support) the idea that the Si III absorption in intervening metal-systems traces metal-enriched gas within a wide range of physical conditions including a) a denser (partly neutral) phase also traced by Si II and other low ions; and b) a more diffuse (predominantly ionized) gas phase also traced by Si IV and other high ions. We further discuss these aspects in

Sect. 7 where we model the ionization conditions in Si III/Si IV absorbers in detail.

In a recent C IV-selected survey of absorbers at $z \leq 0.16$ Burchett et al. (2015) find very similar relations between Si II, Si III, and Si IV in their absorber sample (their Figs. 15 and 16).

5. On the expected cross section of metal-enriched gas in galaxy halos

Before we investigate in detail the observed relation between Si III absorbers and galaxies in a statistical sense, we first set up a geometrical model to estimate the expected cross section of metal-enriched gas in the extended gaseous halos of galaxies at $z = 0$.

Under the assumption that *all* intervening Si III absorbers at low z are related to metal-enriched gas situated in the extended halos of galaxies, the observed number density of Si III absorbers can be directly linked to the space density of galaxies, ϕ , and the effective (geometrical) cross section of the absorbing gas, which is a product of the projected area covered by the gaseous halo $A_{\text{halo}} = \pi r_{\text{halo}}^2$ and the mean covering fraction $\langle f_c \rangle$ of the gas phase that is seen in absorption:

$$\frac{dN}{dz} = \phi \langle f_c \rangle A_{\text{halo}} \frac{c(1+z)^2}{H(z)}. \quad (2)$$

The Hubble parameter is defined as $H(z) = H_0(\Omega_m(1+z)^3 + \Omega_\Lambda)^{1/2}$, which is appropriate for a matter-dominated flat

Universe with a cosmological constant. Eq. (2), and modified versions of it, have been commonly used to estimate the sizes of galaxy halos and the covering fractions of individual ions from QSO absorption-line observations (e.g., Kapczrak et al. 2008; Richter et al. 2011; Prochaska et al. 2011).

We here take the opposite point of view and pose the following question: what would be the expected number density of intervening metal absorbers, if all galaxies at $z = 0$ contain detectable metal-enriched gas in their halos that extends exactly to their respective virial radii?

Using Eq. (2) it is indeed relatively straight-forward to set up a “toy model” for the absorption cross section of extended halo gas taking into account the observed space density and luminosity/mass distribution of galaxies at low redshift. The motivation for such a reverse approach is rather simple: if we could know the maximum contribution of metal-enriched gas that is gravitationally bound to galaxies to the number density of intervening metal absorbers, we would have an important reference value for the interpretation of the observed number densities of intervening Si III systems and their origin in the CGM and/or IGM.

Both the galaxy density ϕ as well as the distribution of the galaxies’ virial radii at $z = 0$, i.e., the most important parameters to calculate dN/dz via Eq. (2), can be obtained indirectly from the local galaxy luminosity function. We here adopt the g -band SDSS luminosity function from Montero-Dorta & Prada (2009), who give Schechter parameters of $\alpha = -1.10$ and $\phi^* = 1.25 \times 10^{-2} h^3 \text{ Mpc}^{-3}$ for $h = 1.0$. We transform these parameters to the cosmological frame defined in Sect. 3.3. and calculate $\phi = \phi^* \Gamma(\alpha + 1, L/L^*)$ for different luminosity bins, where Γ is the incomplete gamma function and L^* is the characteristic luminosity that characterizes the cut-off for the power-law component in the Schechter luminosity function (Schechter 1976).

The key assumption in our toy model is that all halos of galaxies with luminosities $L \geq 0.001 L^*$ contain metal-absorbing gas within their virial radii (R_{vir}). We initially assume a unity covering fraction of the absorbing gas, so that the effective absorption cross section is simply πR_{vir}^2 . Also the virial radius of a galaxy can be inferred indirectly from its luminosity. As recently discussed by Stocke et al. (2014), halo matching models provide a relatively well-defined relation between R_{vir} and L that can be used to define a scaling relation between these two parameters. We define $C = \log(L/L^*)$ and approximate the relation between L and R_{vir} shown in Stocke et al. (their Fig. 8) by the fit

$$\log R_{\text{vir}} = 2.257 + 0.318 C + 0.018 C^2 - 0.005 C^3. \quad (3)$$

Equipped with these relations we can now assign to each luminosity bin a galaxy space density $\phi(L)$ and an effective absorption cross section $A(L) = \pi R_{\text{vir}}^2(L)$, which is all we need to calculate the expected number density of absorbers $dN/dz(L)$ for the same bin. Integration over all galaxy luminosity bins then provides the expected total number density of absorbers arising from the halos of these galaxies.

Figure 8 summarizes the main results from our modeling. The red solid line in the upper panel visualizes the $L - R_{\text{vir}}$ -relation defined by Eq. (3), while the green-shaded histogram indicates the same relation in bins of $\log(L/L^*) = 0.5$. In the middle panel of Fig. 8 the logarithmic galaxy density ($\log \phi(L)$) is plotted against $\log(L/L^*)$ (same binning), while in the lower panel we show the expected number density of absorbers $dN/dz(L)$ (assuming a unity covering fraction, $\langle f_c \rangle = 1$) as a function of $\log(L/L^*)$ for the same binning. By integrating over the desired luminosity range we obtain an estimate for the

Fig. 8. Predictions from the halo model described in Sect. 5. *Upper panel:* the virial radius of galaxies as a function of galaxy luminosity (adapted from Stocke et al. 2014). *Middle panel:* Galaxy space density as a function of galaxy luminosity (from Montero-Dorta & Prada 2009). *Lower panel:* expected number density of CGM absorbers as a function of galaxy luminosity.

total number density of absorbers that arise in the gaseous halos of the galaxies in that luminosity range.

While our observational galaxy sample is restricted to relatively bright galaxies (see Sect. 3), we here consider the much larger range $L/L^* \geq 0.001$ to evaluate the potential contribution of faint galaxies and their halos to the total cross section of intervening metal absorbers, even if they remain unseen in galaxy surveys. For $L/L^* \geq 0.001$ and unity covering fraction we obtain a total absorber number density of $dN/dz = 3.6$. If we include the mean covering fraction as free parameter (which then represents an area-weighted mean), we can write more generally:

$$dN/dz = 3.6 \langle f_c \rangle. \quad (4)$$

For realistic gas covering fractions in galaxy halos in the range $\langle f_c \rangle = 0.1 - 1.0$ this absorber number density is remarkably close to the observed number density of intervening Si III absorbers, as discussed in the previous section.

One serious concern about the relevance of the above given estimate is, how strongly the derived absorber number density depends on the input parameters from the adopted galaxy luminosity function. To explore this dependence we have calculated dN/dz for a whole set of (realistic) Schechter parameters, as presented in Table 1. For this, we vary for a given slope α in each row the normalization density from ϕ_{min}^* over ϕ_{pref}^* to ϕ_{max}^* (where

Table 1. Models for absorber cross sections based on Eq. (2).

Model	α	$\phi_{\min}^*$ [$h^3 \text{ Mpc}^{-3}$]	ϕ_{pref}^* [$h^3 \text{ Mpc}^{-3}$]	$\phi_{\max}^*$ [$h^3 \text{ Mpc}^{-3}$]	$dN/dz_{\min}$	dN/dz_{pref}	$dN/dz_{\max}$
1	-1.00	0.0075	0.0125	0.0175	1.81	3.02	4.23
2	-1.10	0.0075	0.0125	0.0175	2.18	3.64	5.09
3	-1.20	0.0075	0.0125	0.0175	2.73	4.56	6.38
4	-1.30	0.0075	0.0125	0.0175	3.58	5.97	8.35

Notes. The following Schechter parameters are given: α = slope of the power-law component; ϕ^* = normalization density; the preferred parameter combination is indicated with the bold-face font.

$\phi_{\text{pref}}^* = 0.0125 h^3 \text{ Mpc}^{-3}$ represents our preferred normalization; see above) and calculate the expected absorber number densities $dN/dz_{\min}$, dN/dz_{pref} , $dN/dz_{\max}$. For Schechter parameters in the range $\alpha = [-1.0, -1.3]$ and $\phi^* = [0.0075, 0.150]$ the expected number densities vary between $dN/dz = 1.81$ and 8.35. It is therefore valid to claim that the expected contribution of the metal-enriched CGM to the cross section of intervening metal absorbers is $dN/dz < 9$ (this conclusion holds for any metal ion that can be observed via QSO absorption spectroscopy).

One may argue that the values for dN/dz estimated in this manner over-estimate the true absorption-cross section of gaseous halos because galaxy halos can overlap with each other (in particular satellite galaxies and their hosts), so that the effective halos cross section of a galaxy ensemble would be smaller than the sum of A for all individual galaxies in that ensemble. This effect is commonly investigated in studies that aim at characterizing the relationship between the stellar masses of galaxies and their superordinate dark matter (DM) halos, e.g., by using statistical methods such as the Halo Occupation Distribution (HOD) formalism and others (e.g., Peacock & Smith 2000; Moster et al. 2010). From these models follows that, on average, only the most massive halos (with DM halo masses $> 10^{11.8} M_{\odot}$, corresponding to $L > 2 L^*$) are occupied by more than one galaxy. These halos are rare, however, and their contribution to dN/dz is small (see Fig. 8), so that a small change in the absorption cross section of such massive halos basically would have no influence on the estimate of the integrated number density of intervening absorbers.

A comparison between the estimated gas cross section of galaxy halos from our model with the observed number density of intervening Si III absorbers allows us to draw some very interesting conclusions. The first important conclusion is that, because $dN/dz(\text{Si III}) < dN/dz(\text{model})$ for $\log N(\text{Si III}) > 12.2$, the entire population of these Si III systems can be explained by metal-enriched gas that is gravitationally bound to galaxies, i.e., there is no need for an intergalactic gas component that hosts Si III absorbers at this strength. Turning this argument around, our model also predicts that intervening metal absorbers with number densities $dN/dz > 9$ (e.g., O VI absorbers with $dN/dz \approx 16$; Tripp et al. 2008) must partially arise from gas outside of the virial radius of galaxies. This aspect is further discussed in Sect. 8. A second conclusion is that for our preferred model with $\alpha = -1.1$ and $\phi^* = 0.0125 h^3 \text{ Mpc}^{-3}$ (Montero-Dorta & Prada 2009) the mean covering fraction of Si III within R_{vir} is expected to be $\langle f_c \rangle = 2.5 \pm 0.4 / 3.6 = 0.69 \pm 0.11$, a value that is similar to the covering fraction of Si III in the halo of the Milky Way, as recently derived from QSO absorption-line observations (Herenz et al. 2013; Lehner et al. 2012). In Sect. 6 we further investigate, whether the observed distribution of galaxies around Si III absorbers is in line with these conclusions.

Fig. 9. CGM absorption fraction as a function of impact parameter, as predicted from the halo model described in Sect. 5.

Our model further allows us to predict the mean absorption fraction around galaxies as a function of impact parameter ρ . We here define the mean absorption fraction as the detection rate of intervening absorption from CGM gas for a given impact parameter for a population of galaxies with different virial radii. Only the most luminous galaxies with large R_{vir} are expected to contribute to the mean absorption at $\rho > 100$ kpc, while for small impact parameters $\rho < 50$ kpc both luminous as well as faint galaxies do contribute. Consequently, the mean absorption fraction around galaxies is expected to decline in a way that is determined by the distribution of R_{vir} (and thus by the shape of the galaxy luminosity function).

In Fig. 9 we show the mean absorption fraction plotted against ρ (in bins of 50 kpc), as derived from our preferred model with Schechter parameters $\alpha = -1.1$ and $\phi^* = 0.0125 h^3 \text{ Mpc}^{-3}$. As expected, the absorption rate decreases rapidly with increasing impact parameter because the fraction of sightlines that pass galaxies at $\rho > R_{\text{vir}}$ increases. Figure 9 can be directly compared to the observed absorption rate around low-redshift galaxies, as is presented in Sect. 6.

Another important piece of information that can be extracted from our model concerns the expected covering fraction of circumgalactic gas around a population of galaxies in a given luminosity range. It is useful to transform the absorption rate into an effective covering fraction, $\langle \mathcal{F}_c(r_{\text{max}}) \rangle$, that is normalized to a fixed radius r_{max} (instead of being normalized to R_{vir} , which depends on the galaxy's mass and luminosity). To carry out this transformation we need to take into account that the covering fraction describes the detection rate per unit area. Since the area of each ring with thickness Δr and radius r is $\Delta r 2\pi r$, the absorption rates need to be weighted with r and integrated from $r = 0$ to $r = r_{\text{max}}$ to obtain $\langle \mathcal{F}_c(r_{\text{max}}) \rangle$. In this way, it is possible to predict from our model the effective covering fractions for different values of r_{max} for a population of galaxies in a given luminosity range. In Table 2 we list the predicted effective CGM covering

Table 2. Model predictions for effective CGM covering fractions, $\langle \mathcal{F}_c(r_{\max}) \rangle$, for different halo radii and galaxy luminosities (see Sect. 5).

$r_{\max}$ [kpc]	$\langle f_c \rangle$	$\langle \mathcal{F}_c(r_{\max}) \rangle$			
		L/L^* ≥ 0.001	L/L^* ≥ 0.01	L/L^* ≥ 0.1	L/L^* ≥ 1
200	1.00	0.18	0.27	0.48	1.00
400	1.00	0.04	0.07	0.12	0.31
1000	1.00	0.01	0.01	0.02	0.05
200	0.75	0.13	0.20	0.36	0.96
400	0.75	0.03	0.05	0.09	0.23
1000	0.75	0.01	0.01	0.01	0.04
200	0.50	0.09	0.14	0.24	0.62
400	0.50	0.02	0.03	0.06	0.16
1000	0.50	0.00	0.01	0.01	0.02

fractions for different values of $r_{\max}$, $\langle f_c \rangle$, and different luminosity ranges based on the preferred parameters for the galaxy luminosity function (see Table 1). We would like to emphasize again that in this approach $\langle \mathcal{F}_c \rangle$ describes the average CGM covering fraction of a population of galaxies within an annulus with a fixed radius, while $\langle f_c \rangle$ describes the mean covering fraction of the galaxies' CGM within R_{vir} .

6. Observed absorber-galaxy connection

6.1. Individual galaxies associated with Si III absorbers

To characterize the true absorber-galaxy connection at $z \leq 0.1$ we have calculated the geometrical impact parameters ρ between the sightlines that exhibit Si III absorbers at $z \leq 0.1$ in our COS data and nearby galaxies in our galaxy catalog (see Sect. 3.3).

Ideally, one would study the relation between absorbers and galaxies using the absorber-galaxy cross-correlation function together with a well-defined galaxy completeness function. Our galaxy sample, that is based on many different galaxy surveys and individual observations, is highly inhomogeneous with respect to the completeness limit at the faint end of the B -band magnitude distribution, however, and therefore a statistically meaningful galaxy completeness function cannot be obtained. We would like to point out, however, that the motivation for including these galaxy data in our study is not to provide a statistically complete sample of absorber/galaxy pairs, but to qualitatively check the plausibility of our hypothesis, in which most Si III absorbers at $z \leq 0.1$ arise in the extended gaseous halos of luminous low-redshift galaxies, for which the present galaxy data sample is sufficient in depth.

Because of the above mentioned limitations we cannot simply combine the impact-parameter distributions of the individual sightlines to statistically investigate the overall absorber-galaxy connection, but instead have to evaluate the connection between absorbers and galaxies along each sightline individually before combining the results. In the following, we further specify our strategy how to do this.

For each sightline that contains an intervening Si III absorber we first selected all galaxies that have recession velocities within $|\Delta v| = 1000 \text{ km s}^{-1}$ of the absorber (hereafter referred to as “LOS absorber sample”) and identified the galaxy with the smallest impact parameter to the sightline. For the same line of sight we then created a set of nine galaxy control samples covering the adjacent velocity range $|\Delta v| = 1000\text{--}10\,000 \text{ km s}^{-1}$, where each LOS control sample spans a velocity range of

$|\Delta v| = 1000 \text{ km s}^{-1}$, similar as for the LOS absorber sample. We again marked the galaxies that are nearest to the LOS. The galaxy samples constructed in this way have the same magnitude completeness for each sightline.

If intervening absorbers would trace the CGM of galaxies that are close to the sightlines (as we suspect), one would expect for a large-enough absorber/galaxy sample (as provided here) that the impact parameters of the nearest galaxy to the LOS in the absorber samples are, on average, substantially smaller than in the control samples. Such a trend is indeed seen in our data: for 76 percent of the LOS that exhibit an intervening Si III absorber, the galaxy with the smallest impact parameter is located within 1000 km s^{-1} of the absorption redshift.

In the upper panels of Fig. 10 (gray-shaded histograms) we show the distribution of ρ for the nearest galaxies in the LOS absorber samples (“galaxy/absorber sample”) for all sightlines with Si III absorbers (left column) and for the bias-corrected set of sightlines with Si III absorbers (right column). Obviously, galaxies cluster around sightlines if an Si III absorber is present. This trend is evident in both galaxy/absorber samples (total sample and bias-corrected sample), but in the (biased) total sample there are more data points in the lowest ρ -bin, as is expected from the design of the Bordoloi et al. (2014) COS-Dwarfs survey (see Sect. 4.2).

Still, in the bias-corrected galaxy/absorber sample, 56 percent of the galaxies are located at impact parameters $\rho < 200 \text{ kpc}$ and for the same percentage the velocity difference between the galaxy and the absorber is $|\Delta v| \leq 300 \text{ km s}^{-1}$. From our model we would expect that the maximum impact parameter in an idealized galaxy sample is $\rho \approx 300 \text{ kpc}$, as this length scale corresponds to the virial radius of the most luminous galaxies that are expected to significantly contribute to the number density of Si III absorbers before the galaxy-density distribution breaks down for higher luminosities (Fig. 8, middle panel). However, since our galaxy sample is incomplete and highly inhomogeneous along the different LOS with respect to galaxies at the faint end of the luminosity function, the observed distribution of ρ extends much further out. With the green-shaded histogram we show in Fig. 10 the absolute B -band magnitudes for the galaxies in the galaxy/absorber samples, as calculated from their cosmological distance. The dotted line indicates the absolute B magnitude of an L^* galaxy (adopted from Montero-Dorta & Prada 2009).

To check the statistical significance of this clustering trend we analyzed the galaxies in the respective control samples in a similar manner. We find that the galaxies do not cluster around the sightlines in any of the control samples, but their impact parameters are more or less evenly distributed. To demonstrate this, we show in the lower left and right panels of Fig. 10 the impact-parameter distributions in the control samples, i.e., for galaxies that have no absorption systems within $|\Delta v| = 1000 \text{ km s}^{-1}$. For this, we combined for each of the two data sets (total sample/bias-corrected sample) the nine individual control samples to one “composite control sample”, respectively, which contains all galaxies within the velocity window $|\Delta v| = 1000\text{--}10\,000 \text{ km s}^{-1}$ with respect to the absorber redshift (see above).

The distributions of absolute B -band magnitudes in the composite control samples (Fig. 10, lower left panel, green-shaded areas) are similar to those in the galaxy/absorber samples, proving that the different galaxy samples have the same completeness in B .

In summary, the observed absorber-galaxy relation strongly suggests that the galaxies “know” about the presence of nearby

Fig. 10. *Upper panels:* distributions of impact parameters and absolute B -band magnitudes for galaxies that are located within $|\Delta v| = 1000 \text{ km s}^{-1}$ of the absorbers (galaxy/absorber samples). On the *left-hand side* we show the distributions for all sightlines that exhibit Si III absorption, while on the *right-hand side* only the bias-corrected set of sightlines is considered (see Sect. 4.2). Galaxies tend to cluster around the LOS in velocity regions where intervening absorption is observed. *Lower panels:* the same distributions for galaxies that have no absorption systems within $|\Delta v| = 1000 \text{ km s}^{-1}$ (composite control samples; see Sect. 6.2 for details). No clustering is observed in this case.

Si III absorption systems. This is exactly what would be expected if the absorption were (predominantly) caused by metal-enriched gas in the extended halos and the superordinate cosmological environment of these galaxies.

For our bias-corrected galaxy/absorber sample we calculate effective covering fractions of $\langle \mathcal{F}_c(r_{\text{max}}) \rangle = 0.08$ for $r_{\text{max}} = 400 \text{ kpc}$ and $\langle \mathcal{F}_c(r_{\text{max}}) \rangle = 0.01$ for $r_{\text{max}} = 1000 \text{ kpc}$. These effective covering fractions are comparable to those expected for a population of $L > 0.1 L^*$ galaxies that are surrounded by a CGM that reaches out to R_{vir} with $\langle f_c \rangle = 0.75$ (Table 2).

6.2. Absorption strength vs. impact parameter

In Fig. 11 we plot the restframe equivalent widths of Si III $\lambda 1206$ versus the impact parameters of the galaxies nearest to the absorbers. For $\rho < 200 \text{ kpc}$ the equivalent width scatters strongly in the range 10–1000 mÅ. For increasing impact parameters the maximum value for W_r (hereafter referred to as $W_{r,\text{max}}$) is decreasing to values $< 100 \text{ mÅ}$ for $\rho > 500 \text{ kpc}$.

The interpretation of this plot is not as simple as it may look like: because of the incompleteness of the galaxy sample, the largest values for ρ (which are far beyond the virial radii of the

most massive galaxies) do not represent true impact parameters to the nearest galaxies, but rather indicate the impact parameters to the nearest luminous galaxies. From observations of strong Mg II absorbers it is known that the mean Mg II $\lambda 2796$ equivalent width in the CGM of luminous galaxies is larger than for low-luminosity galaxies (e.g., Nielsen et al. 2013). Assuming that a similar trend holds for Si III, the large scatter for W_r (Si III $\lambda 1206$) at $\rho < 200 \text{ kpc}$ can be interpreted by the large range in luminosities of the galaxies whose circumgalactic gas causes the absorption, where $W_{r,\text{max}}$ is determined by the most luminous galaxies. The decline of $W_{r,\text{max}}$ for increasing ρ then simply reflects the decreasing likelihood to miss luminous galaxies around the absorbers that are responsible for the strongest absorbers. For large values of ρ , only absorbers with small W_r values remain, as they belong to low-luminosity galaxies that are too faint to be covered in our galaxy sample.

6.3. QSO sightlines associated with individual galaxies

We now investigate the absorber/galaxy-connection from the perspective of the galaxies. For each galaxy in our sample we first identified QSO sightlines that pass the galaxy at impact

Fig. 11. Restframe equivalent widths of Si III $\lambda 1206$ are plotted against the impact parameters of the galaxies nearest to the absorbers. For increasing impact parameters the maximum value for W_r is decreasing from $W_r \approx 900$ mÅ down to values < 100 mÅ.

Fig. 12. Absorption fraction (fractional abundance of intervening absorbers per galaxy) as a function of impact parameter, as measured in our galaxy/absorber sample.

parameters $\rho < 1000$ kpc. We then further selected only galaxies in redshift ranges that are covered by each relevant COS spectrum at a S/N that is high enough to detect Si III absorption at column densities $\log N_{\text{lim}}(\text{Si III}) \geq 12.2$. Finally, we calculated for each 100 kpc wide impact-parameter bin the absorption fraction (i.e., the fraction of galaxies having a Si III absorber above this column density limit in this impact-parameter range). The result from this analysis is shown in Fig. 12. As can be seen, the observed absorption fraction is substantially smaller than the one derived from the idealized halo model (Fig. 9), but extends to much larger impact parameters even beyond the expected virial radii of massive galaxies. We again interpret this behavior as a sign for the incompleteness in our galaxy data, i.e., we suspect that sightlines that have apparent galaxy impact parameters in the range $300 \leq \rho < 1000$ kpc are arising from halo gas within the virial radii of unseen galaxies.

7. Ionization conditions

7.1. Model setup

To gain insight into the physical properties of the intervening Si III absorbers and to estimate the total gas mass that they trace we studied the ionization conditions in the absorbers using the ionization code Cloudy (v13.03; Ferland et al. 2013). The absorbers are modelled as plane-parallel slabs with fixed neutral gas column densities; they are exposed to the UV background radiation with $\log \Gamma = -13.6$ (see Sect. 2 for more details on the used UV background field) and are assumed to be optically thin in H I.

In Sect. 4 we have suggested that Si III traces at least two characteristic gas phases, a more ionized, diffuse phase that is also traced by Si IV, and a more dense (partly neutral) phase that is also detected in Si II. For our Cloudy modeling we therefore have focused on the relation between the column densities of H I, Si II, Si III, and Si IV as a function of the ionization parameter U , the ratio between ionizing photon density and total particle density (i.e., $U = n_\gamma/n_H$). For an assumed ionizing radiation field one can calculate n_γ and thus can relate U with the gas density n_H .

In Figure 13 we have plotted (as an example) the expected H II, Si II, Si III, and Si IV column densities against $\log n_H$ for a (typical) H I column density of $\log N(\text{H I}) = 15$, based on a set of Cloudy models assuming solar abundances of all heavy elements (Asplund et al. 2009). We also show the expected trend for Mg II, which follows Si II very closely over the entire density range. This similarity justifies our previous approach to estimate the number density of strong Mg II using Si II as a proxy (Sect. 4.3.2). We have set up a grid of Cloudy models in which we have varied the H I column density in the range $\log N(\text{H I}) = 14-19$ to provide column-density predictions for the above listed ions.

The most important conclusion from this modeling is that the shapes of the column-density curves for H II, Si II, Si III, Si IV, and Mg II (and their positions relative to each other) basically do not depend on $\log N(\text{H I})$, implying that the observed column density ratios of the Si ions can be used to constrain n_H in optically thin H I/Si III absorbers even without knowing $N(\text{H I})$.

Figure 13 further indicates that Si IV becomes the dominant ion of Si only for relatively low gas densities ($\log n_H < -3.5$), while Si III dominates in the density range $-3.5 < \log n_H \leq -2.0$. Si II is dominant at $\log n_H > -2.0$, thus at densities that are expected to be relevant only for DLAs and sub-DLAs in the neutral gas disks and in predominantly neutral gas structures in the inner halos of galaxies (e.g., in high-velocity clouds).

7.2. Single-phase model

One may assume that the simultaneous absorption of Si II, Si III, and Si IV at similar radial velocities, such as observed in some systems, stems from a single gas phase in the absorbers. For that case, our Cloudy models provide some firm predictions for the allowed column-density ranges for these three ions that can be summarized by the following parametrization of the expected column-density ratios Si III/Si IV and Si III/Si II in a single gas phase:

$$\log \left[\frac{N(\text{Si III})}{N(\text{Si IV})} \right] = 1.68 - 1.44 \log \left[\frac{N(\text{Si III})}{N(\text{Si II})} \right]. \quad (5)$$

In Fig. 14 we have plotted the observed column-density ratios of these ions (and relevant limits) together with predictions from

Fig. 13. Predictions of H II, Si II, Si III, Si IV, and Mg II column densities as a function of the gas density ($\log n_{\text{H}}$) for an H I column density of $\log N(\text{H I}) = 15$, based on a Cloudy ionization model using the local UV background and assuming absolute and relative solar abundances of all elements. The gray-shaded area indicates the density that is typical for the Si III/Si IV phase (see Sect. 7.3).

the Cloudy model as given in Eq. (5) (the model is indicated in Fig. 14 by the black solid line). For none of the systems that have measured column densities for Si II, Si III, and Si IV (Fig. 14 filled circles) do the data points lie on the expected relation for the single-phase model. For all systems for which we have measured values in these three ions the Si II and/or Si IV column densities are too high for the observed Si III column density to match the single-phase model. While we cannot exclude that at least some of the systems for which only lower limits for Si III/Si IV and Si III/Si II are available are in accordance with the single-phase model, the observations clearly do not favor such a scenario, but rather point towards a more complex multiphase nature of gas, as considered below.

7.3. Multi-phase model

The alternative (and probably more realistic) model for the absorbers is that of a multiphase gas, where Si II and Si IV predominantly trace different gas phases (and different physical regions) that coexist within the same overall absorbing gas structures. In the Milky Way halo, the existence of multiphase halo gas as traced by various low, intermediate, and high ions is well established (e.g., Sembach et al. 2003; Fox et al. 2006; Collins et al. 2009; Shull et al. 2009; Richter et al. 2009; Herenz et al. 2013).

For the following we assume that Si III absorption arises in both a diffuse ionized gas phase traced by Si IV/Si III as well as a somewhat denser (partly neutral) gas phase traced by Si II/Si III. To further investigate the characteristic densities of these two phases we have plotted in Fig. 15 the column densities

Fig. 14. Column-density ratios of Si III/Si II vs. Si III/Si IV are plotted together with predictions from the single-phase Cloudy model (Eq. (5), indicated by the black solid line). Measured values are plotted with filled circles, limits are indicated with open circles. For none of the systems do the data points lie on the expected relation for the single-phase model, implying that the gas is multiphase.

$\log N(\text{Si III})$ vs. $\log N(\text{Si IV})$ (upper panel) and $\log N(\text{Si III})$ vs. $\log N(\text{Si II})$ (lower panel). Data points from measured column density limits in these ions are plotted with open circles. Because both gas phases defined above may be present in an absorber, the plotted values of $\log N(\text{Si III})$ have to be regarded as an upper limit for the Si III column in each phase.

For the absorbers that are detected simultaneously in Si III and Si IV (upper panel of Fig. 15, filled circles) the data points scatter within ~ 0.7 dex around the $N(\text{Si III}) = N(\text{Si IV})$ line. For the absorbers that are detected simultaneously in Si III and Si II (lower panel of Fig. 15, filled circles) the measured Si II column densities are typically lower than that of Si III, but (again) note that a considerable fraction of the Si III column may arise in the Si IV phase, so that $\log [N(\text{Si II})/N(\text{Si III})]$ could be much higher locally.

Because of the unknown intrinsic structure of each absorber it is challenging to provide firm predictions for the gas density for each individual system that has measured Si II/Si III/Si IV column densities. From the exploration of the parameter space the Cloudy models deliver, however, a characteristic gas density that separates the Si IV/Si III from the Si II/Si III phase in the absorbers (see also Fig. 13). We find that the Si IV/Si III phase traces gas with densities $\log n_{\text{H}} \leq -3.0$ (in Fig. 13 indicated with the gray-shaded area), while the Si II/Si III phase has higher densities in the range $\log n_{\text{H}} > -3.0$.

7.4. Total gas mass and baryon budget

Our observations and Cloudy models imply that Si III traces diffuse (predominantly ionized) gas in the extended gaseous halos (i.e., in the circumgalactic medium) of galaxies. An interesting question is, how much mass is contained in such gas and what is the overall baryon budget of intervening Si III absorbers and the metal-enriched CGM. To derive the total gas mass of the Si III systems in our sample we need to calculate the amount of ionized hydrogen in each absorber. Because of the much higher

Fig. 15. Distribution of logarithmic column densities in the Si III absorbers. *Upper panel:* Si IV vs. Si III (absolute values indicated with filled circles, limits with open circles). *Lower panel:* Si II vs. Si III. The dotted/solid lines indicate ratios of +0.5, 0, -0.5 dex, respectively.

ionization fraction in the Si IV/Si III systems compared to the Si II/Si III phase we here concentrate on the estimate of $N(\text{H II})$ in low-density Si III absorbers that are associated with Si IV.

For the range $\log N(\text{H I}) = 14\text{--}17$ our Cloudy model grids imply a relatively simple relation between the minimum H II column density and the Si III column density in each absorber:

$$\log N(\text{H II}) \approx \log N(\text{Si III}) + \log Y - \log (\text{Si}/\text{H})_{\odot}, \quad (6)$$

where the parameter Y , that solely depends on the gas density, needs to be determined from the observed Si IV/Si III ion ratios (Fig. 13). Since we do not know what fraction of the Si III column density can be assigned to the Si IV phase, we can only place a lower limit to Y (see above). Similarly, because of the unknown metallicity of the CGM, we have to assume an upper limit for the silicon abundance (Si/H) in the gas. Equation (6) allows us to derive a lower limit for $N(\text{H II})$ in each Si IV/Si III absorber, from which the integrated (=total) column density, $N(\text{H II})_{\text{tot}}$, can then be determined.

The cosmological mass density of the Si IV/Si III absorbers in terms of the current critical density, ρ_c , can be estimated by

$$\Omega_b(\text{Si III}) \equiv \frac{\mu m_{\text{H}} H_0}{\rho_c c} N(\text{H II})_{\text{tot}} \Delta X_{\text{tot}}^{-1}, \quad (7)$$

with $\mu = 1.3$, $m_{\text{H}} = 1.673 \times 10^{-27}$ kg, $H_0 = 69.7$ km s $^{-1}$ Mpc $^{-1}$ (Hinshaw et al. 2013), and $\rho_c = 3H_0^2/8\pi G$. The comoving path

length ΔX available for the detection of Si IV/Si III absorbers along each sightline is given by:

$$\Delta X \equiv (1+z)^2 [\Omega_m(1+z)^2 + \Omega_{\Lambda}]^{-1/2} \Delta z_{\text{abs}}. \quad (8)$$

The integration over all sightlines then delivers ΔX_{tot} . For our bias-corrected Si IV/Si III absorber sample with $\log N(\text{Si III}) \geq 12.2$ we have $N(\text{H II})_{\text{tot}} \geq 5.4 \times 10^{20}$ cm $^{-2}$ and $\Delta_{\text{tot}} X = 20.65$. The cosmological mass density can then be written as $\Omega_b(\text{Si III}) \geq 4.6 \times 10^{-4} Z_{\text{Si}}$, where Z_{Si} is the Si abundance in the gas relative to the solar value, $\log (\text{Si}/\text{H})_{\odot} = -4.49$ (Asplund et al. 2009). Thus, if the CGM traced by Si III would have a solar Si abundance, it would contain roughly as much mass as the neutral ISM within galaxies at $z = 0$ ($\Omega_b(\text{H I}) = 4.7 \pm 0.7 \times 10^{-4}$; Zwaan et al. 2005).

On the one hand, $\Omega_b(\text{Si III})$ could be much higher, if the mean metallicity of the gas was substantially lower than solar. This appears plausible if most of the gas originates in the IGM, e.g., as material stemming from accretion flows. Lehner et al. (2013) studied the metallicity distribution of LLS at $z \leq 1$ and found two distinct populations of absorbers with mean metallicities of 0.03 solar (population I) and 0.50 solar (population II). They suggest that population I absorbers represent metal-poor circumgalactic gas from accretion streams, while population II systems trace metal-enriched halo material from galaxy outflows and winds. In view of these results, we assume a value of $Z_{\text{Si}} = 0.5$ as a conservative upper limit for the metallicity of the Si III absorbers in our survey. This value leads to $\Omega_b(\text{Si III}) \geq 9.2 \times 10^{-4}$, roughly twice the value of the neutral ISM within galaxies.

Earlier theoretical and observational studies that addressed the outflow of gaseous material from galaxies and the enrichment of the IGM suggested, on the other hand, that the metals produced within galaxies escape in the form of metal-rich (super-solar, eventually) gas pockets (Mac Low & Ferrara 1999; Rauch et al. 2001; Schaye et al. 2007). Such gas pockets could mimic the absorption properties of intervening metal absorbers, but they would carry only very little mass. While it cannot be excluded that some of the Si III absorbers presented in this study belong to such metal patches with above-solar metallicities, the large overall cross section of circumgalactic Si III together with the expected cosmological metal-mass density at $z = 0$ (e.g., Calura & Mateucci 2004) excludes that a dominating fraction of the circumgalactic Si III absorbers have metallicities above solar.

From the above considerations we conclude that the Si IV/Si III bearing gas phase in the CGM of low redshift galaxies contains (possibly substantially) more baryonic matter than their neutral ISM. This conclusion is supported by previous estimates of the baryon content of the cool, photoionized CGM in the local Universe from the COS-Halos survey (Werk et al. 2014).

8. Discussion

8.1. On the origin of intervening Si III absorbers

Our study indicates a tight spatial correlation between intervening Si III absorbers at $z \leq 0.1$ and the local galaxy population at impact parameters ≤ 400 kpc, suggesting that the majority of these absorption systems arise in the extended gaseous halos of these galaxies. This interpretation is supported by recent HST/STIS and HST/COS observations of Si III absorption in the CGM of the Milky Way (Shull et al. 2009; Collins et al. 2009; Richter et al. 2009; Lehner et al. 2012; Herenz et al. 2013), who show that doubly-ionized Si has the largest absorption cross section of all low, intermediate and high ions with a sky covering fraction of $\langle f_c \rangle \approx 0.7$. While the distances and the

space distribution of Si III absorbers in the Milky Way halo still are unclear (owing to our internal vantage point), Lehner et al. (2015) demonstrated that M31 also exhibits an extended, metal-enriched gaseous halo that gives rise to Si III absorption out to ~ 200 kpc. Finally, other groups that have studied the absorption properties of the CGM for individual galaxies (e.g., Keeney et al. 2013), or pre-selected galaxy samples such as the COS-Halos survey (e.g., Tumlinson et al. 2011, 2013; Werk et al. 2013; Peeples et al. 2013) demonstrate that Si III is ubiquitous in the extended CGM of low-redshift galaxies. The existence of such discrete Si III bearing gas complexes with temperatures $T < 10^5$ K (thus below the virial temperature of their DM host halos) in the extended circumgalactic environment of galaxies can be understood in terms of the steady circulation of hot and cold gas through the CGM (“circumgalactic fountain”) as part of the ongoing galaxy evolution. In this scenario, star formation in galaxies drives out large amounts of (hot) metal-enriched gas. Even if this material leaves the potential well of an individual galaxy, it is trapped by the superordinate cosmological structure. From there, the gas may (slowly) fall back onto the galaxy of its origin in the form of discrete gas structures, as the gas never reaches hydrostatic equilibrium during such a circulation cycle (Ford et al. 2014). Alternatively, the gas may be accreted by a different galaxy nearby, or heated up to the virial temperature of the superordinate DM halo, in which case it may remain extragalactic forever.

While the observed frequency of Si III absorbers with $\log N(\text{Si III}) \geq 12.2$ and the derived impact parameter distribution are in line with a scenario, in which *all* Si III absorbers are located within the virial radius of intervening galaxies and thus are gravitationally bound to them, it cannot be excluded that there exists a population of intervening Si III absorbers that traces gas at larger distances. This is actually expected, since in many cases large, gas-rich spiral galaxies like the Milky Way do not represent isolated systems, but are part of a galaxy group, which binds metal-enriched diffuse gas within its own virial radius in the form of an intragroup medium.

Stocke et al. (2014) recently have studied a class of “warm” H I/O VI absorbers using COS spectra. They suggested that these systems trace an extended (Mpc scale) $T = 10^5\text{--}10^6$ K intragroup medium in spiral-rich galaxy groups. If such warm gas was typical for group environments, it appears plausible that one would find cooler ($T < 10^5$ K) gas patches embedded in such a medium that could give rise to intervening Si III/Si IV absorption. Some of the galaxy/absorber pairs that have apparent impact parameters in the range $\rho = 200\text{--}1000$ kpc may belong to such group absorbers. The Cloudy modeling predicts that Si III/Si IV absorbers trace gas down to thermal pressures of $P/k = n_{\text{H}}T \sim 1 \text{ cm}^{-3} \text{ K}$. For gas that is gravitationally bound to individual galaxies, such low gas pressures would be expected only in the outermost regions of galaxies near their virial radius (see also discussion in Shull 2014). However, such a value for P/k also would be in agreement with the expected range of gas pressures in galaxy groups (Stocke et al. 2013).

Our survey suggests that the number density distribution of Si III absorbers breaks down for column densities $\log N(\text{Si III}) \leq 12.2$ (Fig. 4, right panel), which is not a completeness effect in our data (see Sect. 4.1). These low-column density systems may represent the prime candidates for metal-enriched cloudlets that arise in regions with low gas densities (and pressures), such as in group environments and in the IGM. As pointed out by Stocke et al. (2013), the expected number density of galaxy groups is ten times less than the space density of L^* galaxies (Berlind et al. 2006). Interestingly, the number density of Si III absorbers

with $\log N(\text{Si III}) \leq 12.2$ is also ~ 10 times less than the number density of absorbers with $\log N(\text{Si III}) \geq 12.2$, supporting a scenario in which high-column density Si III systems trace the CGM of galaxies, while low-column density Si III systems arise in the intragroup gas of galaxy groups.

With the occurrence of several galaxies at impact parameters $\rho < 1000$ kpc to the QSO sightlines and with radial velocities close to the observed absorber velocities (such as expected for group environments), the interpretation of the observed absorption with respect to origin and nature of the gas in its galaxy environment generally is tricky. While a more systematic investigation between intervening Si III absorbers and galaxy group environments clearly is beyond the scope of this paper, we show in Fig. 16 as a prominent example the galaxy group environment of the $z = 0.0037$ Si III absorber towards the QSO 1H0419–577 (IRAS F04250–5718). This sightline passes two galaxies in the Dorado galaxy group (Kilborn et al. 2005; Maia et al. 1989) at impact parameters $\rho < 220$ kpc. In principle, the observed Si III absorption at $cz = 1109 \text{ km s}^{-1}$ could be associated with either of these two galaxies, which have radial velocities of $v_r = 1050$ and 1215 km s^{-1} (Kilborn et al. 2005). The observed gas may be infalling or outflowing gaseous material; the metallicity of the absorber lies in the range between 0.1–1.0 solar (as derived from the fit of the H I Ly α absorption together with the Cloudy model of the Si III/Si IV absorption), thus in line with both scenarios. However, the absorber could also be located outside the virial radii of these two galaxies and may belong to a faint (unseen) dwarf galaxy in the same group or may represent a metal-rich gas patch embedded in the intragroup medium of the Dorado group. The interpretation of *individual* absorber/galaxy pairs thus remains inconclusive with magnitude-limited galaxy data. The statistical connection between galaxies and intervening Si III systems, as studied here, yet demonstrates that both class of objects trace the same Mpc-scale environment within the cosmic web.

8.2. Comparison with previous Si III absorption-line studies

We are not aware of any other systematic studies in the literature that focus explicitly on Si III-selected intervening absorption systems and their relation to galaxies. There are, however, several absorption-line surveys at low redshift (using various UV spectrographs) that provide information on the number density of Si III and other intermediate ions (e.g., C III) and the distribution of equivalent widths/column densities of these ions.

Tilton et al. (2012) compiled UV absorption-line data from HST/STIS and FUSE and prepared a catalog of UV absorbers for redshifts $z < 0.4$. From their data sample they derive a number density of intervening Si III absorbers of $dN/dz = 7.4^{+2.1}_{-1.2}$ for $\log N(\text{Si III}) > 12.2$ for this redshift range, based on a total redshift path of $\Delta z \approx 5.2$. This value is more than twice the value derived in this study. The same authors recently published another absorption-line catalog of intervening absorption systems at $z < 0.4$, this time based on HST/COS data of 82 AGN (Danforth et al. 2016). In this new survey, the authors derive a number density of $dN/dz = 5.9^{+0.9}_{-0.6}$ for $\log N(\text{Si III}) > 12.2$. Moreover, their study suggests an *increase* for $dN/dz(\text{Si III})$ for decreasing redshift in the local Universe (their Fig. 15). Their new value again is substantially higher than the value derived by us. To investigate the origin for this discrepancy we have carefully compared their absorber list with ours, as our COS data sample includes all of the 82 QSOs presented in Danforth et al. (2016). We suspect that the higher value for $dN/dz(\text{Si III})$ derived by Danforth et al. (2016) stems from the less stringent selection criteria for

Fig. 16. *Left panel:* distribution of galaxies and HI in the Dorado galaxy group (see Kilborn et al. 2005, and references therein). Intervening Si III absorption is observed at $z = 0.0037$ ($cz = 1109 \text{ km s}^{-1}$) towards the QSO 1H0419–577 (black filled circle). The absorption most likely is associated with the CGM of one group member or with the intergroup medium. *Right panel:* zoom-in for the region around the two group members F157–081 and NGC 1574; the absorber could be associated with either or both of these galaxies given its velocity and projected distance to each of the systems.

identifying metal absorbers and defining the relevant absorption path lengths along their sightlines. Also, a possibly existing selection bias in their QSO sample may be the reason for the higher value of $dN/dz(\text{Si III})$.

We identify three Si III systems in their absorber list, whose identifications are based on absorption features that (in our opinion) most likely have different origins. We also have identified one candidate Si III absorber that is not listed in the Danforth et al. (2016) paper. In Table A.4 in the Appendix we list these discrepant absorption systems together with a short description of the absorption characteristics.

As we discuss in one of the following sections, state-of-the-art hydrodynamical simulations of metal-enriched gas in the local Universe do not support values of $dN/dz > 5$ for Si III absorbers for $\log N(\text{Si III}) > 12.2$, but favour Si III number densities of < 4 for $z \approx 0$.

8.3. Comparison with other CGM studies

As mentioned above, Si III is frequently detected in the CGM of individual galaxies (Keeney et al. 2013; Lehner et al. 2015) and in the CGM of pre-selected galaxy samples (e.g., COS-Halos; Tumlinson et al. 2013; Werk et al. 2013; Liang & Chen 2014). Our study, which represents a statistical rather than a targeted study of the CGM in the local Universe, complements most of the previous observational CGM studies. Many of the COS sightlines that have been used by previous, targeted CGM studies are included in our sample. Because of the statistical nature of our survey, we refrain from comparing our results for individual galaxy/absorber pairs with results from other studies.

From an archival study of CGM absorption around 195 galaxies at $z < 0.176$ Liang & Chen (2014) find a mean Si III covering fraction of $0.60^{+0.13}_{-0.18}$ within $0.54 R_{\text{halo}}$ and $0.14^{+0.11}_{-0.05}$ for the range $0.54\text{--}1.02 R_{\text{halo}}$, but no significant Si III absorption beyond. These covering fractions are lower than our estimate of $\langle f_c \rangle = 0.69 \pm 0.11$. This is not surprising, however, since their study considers only strong Si III systems with

$W_r > 100 \text{ mÅ}$ ($\log N(\text{Si III}) > 12.6$), while our estimate is based on a more sensitive search including weak and strong absorbers with $\log N(\text{Si III}) > 12.2$. If we adopt our measured value of $dN/dz(\text{Si III}) = 1.9$ for $N(\text{Si III}) \geq 12.6$ for our estimate of $\langle f_c \rangle$ using Eq. (4), we obtain a value of $0.47^{+0.09}_{-0.08}$ within R_{vir} , thus in good agreement with the Liang & Chen (2014) estimate. Also Werk et al. (2013) consider only strong Si III absorbers around $L \approx L^*$ absorbers with $W_r > 100 \text{ mÅ}$, and find $\langle f_c \rangle = 0.72^{+0.07}_{-0.17}$ for their total galaxy with little dependence on the galaxy mass or star-formation rate (their Table 6). Within the given error bars, these estimates for $\langle f_c \rangle$ (based on different methods) agree very well with each other.

In contrast, Bordoloi et al. (2014) studied the CGM around dwarf galaxies at $z \leq 0.1$ and found no metal absorption beyond $0.5 R_{\text{vir}}$. Their study suggests that the filling factor of warm circumgalactic gas is substantially smaller for dwarfs than for L^* galaxies. As described in Sect. 4.2, our full data set includes most of the sightlines from the Bordoloi et al. sample, so that we can analyze the Si III absorption fraction in the CGM of these dwarf galaxies directly. We find that only 17 out of the according 40 sightlines show detectable Si III with $\log N(\text{Si III}) > 12.2$ at the redshifts of the dwarf galaxies ($\langle f_c \rangle = 0.43^{+0.10}_{-0.11}$), demonstrating that the absorption fraction of the warm CGM traced by Si III around dwarf galaxies is only ~60 percent of that seen in galaxies with higher luminosities. The small CGM absorption fraction around dwarf galaxies is the reason for the almost identical number densities of intervening Si III in our original data sample and in the bias-corrected sample (Sect. 4.2).

Turning to high-ionization species, Wakker & Savage (2009) have studied the relation between O VI and nearby galaxies at $z < 0.017$ based on UV and FUV data along 76 extragalactic sightlines, demonstrating that a substantial fraction of the O VI systems arise from gas within R_{vir} of these galaxies (see also Prochaska et al. 2011; Tumlinson et al. 2011; Stocke et al. 2013). However, in contrast to Si III, O VI is also present beyond the virial radius of these galaxies, tracing hot metal-enriched gas (at higher gas temperatures and lower densities than Si III) that presumably has been ejected by galactic winds and outflows in past

epochs of active star formation. In fact, in view of our CGM modeling results presented in Sect. 5, the measured O VI number density at low redshifts of $dN/dz(\text{O VI}) \approx 16$ (Tripp et al. 2008) indicates a very large absorption cross section of O VI that is clearly beyond the expected cross section of the CGM in the local Universe, even if non-standard Schechter parameters in the luminosity function are considered (Table 1, fourth row). The Milky Way possibly also contains a massive, extended O VI envelope that reaches deep into the Local Group potential well (Sembach et al. 2003; Wakker et al. 2003).

Interestingly, the detailed analysis of the COS-Halos sample suggests that the absorption properties of low and intermediate ions (such as Si III) in star-forming galaxies do not significantly differ from those in passive galaxies, while O VI predominantly arises in the halo of active galaxies (Thom et al. 2012; Werk et al. 2013; Tumlinson et al. 2011). From their study, Liang & Chen (2014) conclude that the CGM becomes progressively more ionized from small to large radii. A similar conclusion was drawn by us from modeling the radial decline of the neutral gas fraction in the CGM in the Local Group (Richter 2012).

8.4. Comparison with hydrodynamical simulations

Cosmological, hydrodynamical simulations have recently become a powerful tool for studying intergalactic and circumgalactic gas at low and high redshifts (e.g., Oppenheimer & Davé 2006; Crain et al. 2013; Nuza et al. 2014). The line statistics from synthetic absorption spectra generated from such simulations can be directly compared to QSO absorption-line studies to investigate the different gas phases in the IGM and CGM and their redshift evolution (Fang & Bryan 2001; Richter et al. 2006; Fangano et al. 2007; Tepper-García et al. 2011, 2012, 2013; Oppenheimer et al. 2012; Smith et al. 2011; Churchill et al. 2015).

While most of these studies have focused on the properties of high-ion absorbers, such as O VI and Ne VIII, to study the shock-heated warm-hot intergalactic medium or shock-heated gas in the CGM, intermediate ions such as Si III and C III so far have not been considered for a detailed comparison study of absorption-line statistics in simulations and observational data. From the simulations of Smith et al. (2011), Danforth et al. (2016) extracted the cumulative line density of intervening metal absorbers for a comparison with their COS absorption-line survey. While their own value for $dN/dz(\text{Si III})$ of ~ 6 for $\log N(\text{Si III}) > 12.2$ (see Sect. 8.2) lies far above the value predicted by Smith et al. for this column-density limit ($dN/dz(\text{Si III}) \approx 3$), the Si III number density derived by us is in very good agreement with the results by Smith et al.

We here re-use synthetic spectra generated along random LOS from a simulation run (Model AGN) of the Overwhelmingly Large Simulations (OWLS; Schaye et al. 2010) to further investigate the frequency and physical conditions in Si III absorbers at low redshift ($z = 0.25$). Similar simulations have been used by us previously to study absorption signatures of warm-hot gas in the local Universe (Tepper-García et al. 2011, 2012, 2013). The OWLS simulations were set up using the smoothed particle hydrodynamics (SPH) code GADGET III (a modified version of GADGET II; Springel 2005) and were carried in a cubic box of $100 h^{-1}$ comoving Mpc on a side, containing 5123 dark matter (DM) and 5123 baryonic particles. The initial mass resolution is $4.1 \times 10^8 h^{-1} M_\odot$ (DM) and $8.7 \times 10^8 h^{-1} M_\odot$ (baryonic), while the gravitational softening is set to $8 h^{-1}$ comoving kpc and is fixed at $2 h^{-1}$ proper kpc below $z = 3$. The cosmological simulations from the OWLS

project are characterized by a particularly careful implementation of important physical processes that have been largely ignored in earlier studies (e.g., the influence of the photoionization on the cooling function of the gas). Details on the sub-grid physics used in OWLS can be found in Wiersma et al. (2009a; radiative cooling), Schaye & Dalla Vecchia (2008; star formation), Dalla Vecchia & Schaye (2008; stellar feedback), and Booth & Schaye (2009; AGN feedback). The strategy, how the synthetic absorption-line spectra from OWLS were set up and analyzed is presented in Tepper-García et al. (2011, 2012, 2013). In Fig. 17, upper panel, we show the cumulative number density of intervening Si III absorbers as a function of the limiting equivalent width predicted by OWLS (Model AGN). The redshift in the simulation run is higher than the maximum redshift of our data. This is, however, not an issue since we do not expect the gas producing the observed absorption to evolve strongly from $z = 0.25$ to $z = 0.10$. The measured value from this study and from Tilton et al. (2012; T12) and Danforth et al. (2016; D16) are indicated with filled circles. The predicted number density is ~ 1.7 for $\log N(\text{Si III}) > 12.2$ ($\log [W_r(\lambda 1206)/\text{mÅ}] \geq 1.52$), thus only slightly below the observed value of 2.5 ± 0.4 from our COS data set.

It is worth noting that differences between the predicted and observed line-number densities may be alleviated considering that the stellar yields used in the simulations to model the chemical evolution of the gas are uncertain by factors of a few (see Wiersma et al. 2009b). Thus, some modification of the abundances in post-processing would be justified, which would bring the predicted dN/dz into better agreement with our measured value. However, we refrain from doing so because this could break the self-consistency of the simulation if it were to change the cooling rates significantly.

In the lower panel of Fig. 17 we show the phase-space distribution in the temperature-density plane of the Si III-absorbing gas in the AGN run at $z = 0.25$ from OWLS. The typical Si III absorber in the simulation has a temperature of $T \approx 15\,000\text{--}20\,000$ K and a density of $n_{\text{H}} \approx 10^{-4}\text{--}10^{-2} \text{ cm}^{-3}$, in very good agreement with the values estimated with Cloudy from the Si II/Si III/Si IV column-density ratios in our COS absorber sample. The resulting range for the expected thermal gas pressure is $P/k \approx 2\text{--}160 \text{ cm}^{-3} \text{ K}$, thus in a range that is typical for the CGM (Cen 2013).

In conclusion, the AGN model from OWLS and the simulations from Smith et al. (2011) predict absorber properties that are compatible with our observations and in line with the idea, that the majority of the Si III absorbers at $z \leq 0.1$ arise in the extended halos of low-redshift galaxies. For the future, we are planning to further explore the relation between intermediate-ion absorbers and galaxies at low z using higher-resolution simulations from the EAGLE (Evolution and Assembly of GaLaxies and their Environments) project (Schaye et al. 2015).

9. Summary and conclusions

In this paper, we present a systematic study of intervening Si III absorbers and their relation to galaxies in the redshift range $z \leq 0.1$ along 303 QSO sightlines using archival UV spectra obtained with HST/COS. The main results are summarized as follows:

- (1) We detect 69 intervening Si III absorbers in the range $z = 0.00014\text{--}0.09789$ along a total redshift path of $\Delta z \approx 24$. The restframe equivalent widths in the Si III $\lambda 1206$ line lie in the range $W_r = 13\text{--}885 \text{ mÅ}$, corresponding to Si III column densities $\log N(\text{Si III}) > 11.9$. We derive a bias-corrected number density of intervening Si III systems of

Fig. 17. *Upper panel:* cumulative number density of intervening Si III absorbers for different equivalent-width limits predicted by a simulation run from the OverWhelmingly Large Simulations (OWLS; Schaye et al. 2010), as presented in Tepper-García et al. (2012). The measured value from this study and from Tilton et al. (2012; T12) and Danforth et al. (2016; D16) are indicated with filled circles. *Lower panel:* phase diagram of intervening Si III absorbers in the temperature-density plane, as predicted by OWLS.

$dN/dz = 2.5 \pm 0.4$ for absorbers with $\log N(\text{Si III}) \geq 12.2$, suggesting that Si III-selected absorbers outnumber strong Mg II at $z \approx 0$ by a factor of ~ 3 . Weak absorbers in the range $\log N(\text{Si III}) = 11.8\text{--}12.2$ turn out to be rare ($dN/dz \approx 0.3$); they possibly represent an absorber population that is distinct from the one with larger Si III column densities.

- (2) The observed Si III absorption is typically accompanied by absorption from other low and/or high ions. The positive correlations between the equivalent widths of Si III and Si IV and between Si III and Si II indicates that doubly ionized silicon traces gas in a range of physical conditions. This conclusion is supported by Cloudy ionization models of the absorbers, which indicate that Si III arises either in diffuse, ionized low-density ($\log n_{\text{H}} \leq -3$, typically) gas that is also observed in Si IV absorption, or in somewhat denser ($\log n_{\text{H}} \geq -3$, typically), more neutral environments that are also traced by Si II.
- (3) We geometrically model the absorption cross section of diffuse gas within the virial radii (R_{vir}) of galaxies at

$z = 0$ for galaxies in the luminosity range $L/L^* > 0.001$ using the SDSS galaxy luminosity function for $z = 0$ and scaling relations between R_{vir} and L . Our modeling implies that circumgalactic gas within the virial radius of galaxies contributes with $dN/dz < 9$ to the total number density of intervening absorbers, even if a unity covering fraction of the absorbing gas is assumed. If we adopt the SDSS g -band luminosity function as reference (Montero-Dortas et al. 2009), we obtain $dN/dz = 3.6 \langle f_{\text{c}} \rangle$ as expected number density for CGM absorbers from $L \geq 0.001 L^*$ galaxies. In light of this result, the measured value of $dN/dz(\text{Si III}) = 2.5 \pm 0.4$ is in line with the idea, that the majority of the intervening Si III absorbers with $\log N(\text{Si III}) \geq 12.2$ at $z \approx 0$ trace the circumgalactic medium at $R < R_{\text{vir}}$ of nearby galaxies with an average covering fraction of $\langle f_{\text{c}} \rangle = 2.5/3.6 = 0.69$, a value that is in excellent agreement with results from other studies (Liang & Chen 2014; Werk et al. 2013). Our model further predicts that intervening metal absorbers with number densities $dN/dz > 9$ (e.g., O VI absorbers) must partially arise from gas outside of the virial radius of galaxies.

- (4) We compare the Si III absorber redshifts and positions with that of $\sim 64\,000$ galaxies at $z \leq 0.1$ using archival galaxy-survey data. For ~ 60 percent of the absorbers we find possible host galaxies within 300 km s^{-1} of the absorbers and at impact parameters $\rho < 200 \text{ kpc}$, indicating that the spatial distributions of Si III absorbers and galaxies are highly correlated. We verify the significance of this result by studying the distribution of galaxies around the same sightlines in velocity ranges without Si III absorption and find no clustering of the galaxies, as expected. The observed Si III absorption fraction around the galaxies scales differently with impact parameter than predicted by our model. We assign this behavior to the incompleteness in our galaxy sample to identify faint galaxies that are associated with Si III absorbers.
- (5) We estimate the baryon content of the Si III-absorbing gas phase in the CGM at low z using Cloudy ionization models. Assuming that the metallicity of the gas is ≤ 0.5 solar, the cosmological mass density of the gas in Si III absorbers is $\Omega_b(\text{Si III}) \geq 9.2 \times 10^{-4}$. This lower limit is roughly twice the value derived for the HI mass density at $z = 0$, indicating that the diffuse CGM around galaxies, as traced by doubly-ionized Si, contains substantially more baryonic matter than their neutral ISM.
- (6) We discuss the origin of intervening Si III absorption in the CGM of galaxies and in galaxy groups and compare our results with previous absorption-line catalogs and CGM studies at low redshift. We suggest that the majority of the strong Si III absorbers with $\log N(\text{Si III}) \geq 12.2$ typically arise within the extended halos of galaxies within R_{vir} , while weak systems with $\log N(\text{Si III}) < 12.2$ possibly also trace gas at larger distances (e.g., group environments or the IGM). The comparison of our measurements with predictions from cosmological hydrodynamical simulations from the OWLS project and other simulations shows a fair agreement for the absorber number density and the estimated temperature-density range of intervening Si III absorbers.

Acknowledgements. This research used the facilities of the Canadian Astronomy Data Centre operated by the National Research Council of Canada with the support of the Canadian Space Agency. This research also has made use of the SIMBAD database, operated at CDS, Strasbourg, France. We thank Joop Schaye and an anonymous referee for helpful comments and suggestions.

References

- Anderson, M. E., & Bregman, J. N. 2011, *ApJ*, **737**, 22
- Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, *ARA&A*, **47**, 481
- Berlind, A. A., Frieman, J., & Weinberg, D. H. 2006, *ApJS*, **167**, 1
- Birnboim, Y., & Dekel, A. 2003, *MNRAS*, **345**, 349
- Bogdán, Á., Forman, W. R., Kraft, R. P., & Jones, C. 2013, *ApJ*, **772**, 98
- Booth, C. M., & Schaye, J. 2009, *MNRAS*, **398**, 53
- Burchett, J. N., Tripp, T. M., Werk, J. K., et al. 2015, *ApJ*, **815**, 91
- Calura, F., & Mateucci, F. 2004, *MNRAS*, **350**, 351
- Cen, R. 2013, *ApJ*, **770**, 139
- Churchill, C. W., Van der Vliet, J. R., Trujillo-Gomez, S., Kacprzak, G. G., & Klypin, A. 2015, *ApJ*, **802**, 10
- Collins, J. A., Shull, J. M., & Giroux, M. L. 2009, *ApJ*, **705**, 962
- Crain, R. A., McCarthy, I. G., Schaye, J., Theuns, T., & Frenk, C. S. 2013, *MNRAS*, **432**, 3005
- Dai, X., Anderson, M. E., Bregman, J. N., & Miller, J. M. 2012, *ApJ*, **755**, 107
- Danforth, C. W., Tilton, E. M., Shull, J. M., et al. 2016, *ApJ*, **817**, 111
- Debes, J., et al. 2016, Cosmic Origins Spectrograph Instrument Handbook, Version 8.0 (Baltimore, MD: STScI)
- Fang, T., & Bryan, G. L. 2001, *ApJ*, **561**, 31
- Fangano, A. P. M., Ferrara, A., & Richter, P. 2007, *MNRAS*, **381**, 469
- Ferland, G. J., Korista, K. T., Verner, D. A., et al. 1998, *PASP*, **110**, 761
- Fontana, A., & Ballester, P. 1995, *ESO Messenger*, **80**, 37
- Ford, A. B., Davé, R., Oppenheimer, B. D., et al. 2014, *MNRAS*, **444**, 1260
- Fox, A. J., Wakker, B. P., Savage, B. D., et al. 2005, *ApJ*, **630**, 332
- Fox, A. J., Savage, B. D., & Wakker, B. P. 2006, *ApJS*, **165**, 229
- Fox, A. J., Wakker, B. P., Smoker, J. V., et al. 2010, *ApJ*, **718**, 1046
- Green, J. C., Fronging, C. S., Osterman, S., et al. 2012, *ApJ*, **744**, 60
- Haardt, F., & Madau, P. 2012, *ApJ*, **746**, 125
- Herenz, P., Richter, P., Charlton, J. C., & Masiero, J. R. 2013, *A&A*, **550**, A87
- Hinshaw, G., Larson, D., Komatsu, E., et al. 2013, *ApJS*, **208**, 19
- Kacprzak, G. G., Churchill, C. W., Steidel, C. C., & Murphy, M. T. 2008, *ApJ*, **135**, 922
- Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, *A&A*, **440**, 775
- Keeney, B. A., Stocke, J. T., Rosenberg, J. L., et al. 2013, *ApJ*, **765**, 27
- Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, *MNRAS*, **363**, 2
- Kilborn, V. A., Koribalski, B., Forbes, D. A., Barnes, D. G., & Musgrave, R. C. 2005, *MNRAS*, **356**, 77
- Kollmeier, J. A., Weinberg, D. H., Oppenheimer, B. D., et al. 2014, *ApJ*, **789**, L32
- Lehner, N., Howk, J. C., Thom, C., et al. 2012, *MNRAS*, **424**, 2896
- Lehner, N., Howk, J. C., Tripp, T. M., et al. 2013, *ApJ*, **770**, 138
- Lehner, N., Howk, J. C., & Wakker, B. P. 2015, *ApJ*, **804**, 79
- Liang, C. J., & Chen, H.-W. 2014, *MNRAS*, **445**, 2061
- Lundgren, B. F., Brunner, R. J., York, D. G., et al. 2009, *ApJ*, **698**, 819
- Mac Low, M. M., & Ferrara, A. 1999, *ApJ*, **513**, 142
- Maia, M. A. G., Da Costa, L. N., & Latham, D. W. 1989, *ApJS*, **69**, 809
- Maller, A. H., & Bullock, J. S. 2004, *MNRAS*, **355**, 694
- Mo, H. J., & Miralda-Escudé, J. 1996, *ApJ*, **469**, 589
- Montero-Dorta, A. D., & Prada, F. 2009, **399**, 1106
- Morton, D. C. 2003, *ApJS*, **149**, 205
- Moster, B. P., Somerville, R. S., Maulbetsch, C., et al. 2010, *ApJ*, **710**, 903
- Nestor, D. B., Turnshek, D. A., & Rao, S. M. 2005, *ApJ*, **628**, 637
- Nielsen, N. M., Churchill, C. W., & Kacprzak, G. G. 2013, *ApJ*, **776**, 115
- Nuza, S. E., Parisi, F., & Scannapieco, C. 2014, *MNRAS*, **441**, 2593
- Oppenheimer, B., & Davé, R. 2006, *MNRAS*, **373**, 1265
- Oppenheimer, B., Davé, R., Katz, N., Kollmeier, J. A., & Weinberg, D. H. 2012, *MNRAS*, **420**, 829
- Peacock, J. A., & Smith, R. E. 2000, *MNRAS*, **318**, 1144
- Peeples, M. S., Werk, J. K., Tumlinson, J., et al. 2014, *ApJ*, **786**, 54
- Planck Collaboration XIII. 2015, *A&A*, submitted [[arXiv:1502.01589](https://arxiv.org/abs/1502.01589)]
- Prochaska, J. X., Weiner, B., Chen, H.-W., Mulchaey, J., & Cooksey, K. 2011, *ApJ*, **740**, 91
- Prochter, G. E., Prochaska, J. X., Chen, H.-W., et al. 2006, *ApJ*, **639**, 766
- Putman, M. E., Peek, J. E. G., & Joung, M. R. 2012, *ARA&A*, **50**, 491
- Rauch, M., Sargent, W. L. W., Barlow, T. A., & Carswell, R. F. 2001, *ApJ*, **562**, 76
- Rees, M. J., & Ostriker, J. P. 1977, *MNRAS*, **179**, 541
- Richter, P. 2006, *Rev. Mod. Astron.*, **19**, 31
- Richter, P. 2012, *ApJ*, **750**, 165
- Richter, P., Savage, B. D., Wakker, B. P., Sembach, K. R., & Kalberla, P. M. W. 2001, *ApJ*, **549**, 281
- Richter, P., Fang, T., & Bryan, G. L. 2006, *A&A*, **451**, 767
- Richter, P., Charlton, J. C., Fangano, A. P. M., Ben Bekhti, N., & Masiero, J. R. 2009, *ApJ*, **695**, 1631
- Richter, P., Krause, F., Fechner, C., Charlton, J. C., & Murphy, M. T. 2011, *A&A*, **528**, A12
- Savage, B. D., & Sembach, K. R. 1991, *ApJ*, **379**, 245
- Schaye, J., Carswell, R. F., & Kim, T.-S. 2007, *MNRAS*, **379**, 1169
- Schaye, J., Dalla Vecchia, C., Booth, C. M., et al. 2010, *MNRAS*, **402**, 1536
- Schaye, J., Crain, R. A., Bower, R. G., et al. 2015, *MNRAS*, **446**, 521
- Schechter, P. 1976, *ApJ*, **203**, 297
- Sembach, K. R., Wakker, B. P., Savage, B. D., et al. 2003, *ApJS*, **146**, 165
- Shull, J. M. 2014, *ApJ*, **784**, 142
- Shull, J. M., Jones, J. R., Danforth, C. W., & Collins, J. A. 2009, **699**, 754
- Shull, J. M., Moloney, J., Danforth, C. W., & Tilton, E. M. 2015, *ApJ*, **811**, 3
- Smith, B. D., Hallman, E. J., Shull, J. M., & O'Shea, B. W. 2011, *ApJ*, **731**, 6
- 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
- Tepper-García, T., Richter, P., Schaye, J., et al. 2011, *MNRAS*, **413**, 190
- Tepper-García, T., Richter, P., Schaye, J., et al. 2012, *MNRAS*, **425**, 1640
- Tepper-García, T., Richter, P., Schaye, J., et al. 2013, *MNRAS*, **436**, 2063
- Thom, C., Tumlinson, J., Werk, J., Prochaska, J. X., & Tripp, T. 2012, *ApJ*, **758**, 41
- Tilton, E. M., Danforth, C. W., Shull, J. M., & Ross, T. L. 2012, *ApJ*, **759**, 112
- Tripp, T. M., Wakker, B. P., Jenkins, E. B., et al. 2003, *AJ*, **125**, 3122
- Tripp, T. M., Sembach, K. R., Bowen, D. V., et al. 2008, *ApJS*, **177**, 39
- Tumlinson, J., Shull, J. M., Rachford, B. L., et al. 2002, *ApJ*, **566**, 857
- Tumlinson, J., Thom, C., Werk, J. K., et al. 2011, *Science*, **334**, 948
- Tumlinson, J., Thom, C., Werk, J. K., et al. 2013, *ApJ*, **777**, 59
- van de Voort, F., Schaye, J., Booth, C. M., & Dalla Vecchia, C. 2011, *MNRAS*, **414**, 2458
- Wakker, B. P. 2001, *ApJS*, **136**, 463
- Wakker, B. P., & Savage, B. D. 2009, *ApJS*, **182**, 378
- Wakker, B. P., & van Woerden, H. 1998, *ARA&A*, **35**, 217
- Wakker, B. P., Howk, J. C., & Savage, B. D. 1999, *Nature*, **402**, 388
- Wakker, B. P., Hernandez, A. K., French, D., et al. 2015, *ApJ*, **840**, 14
- Werk, J. K., Prochaska, J. X., Thom, C., et al. 2013, *ApJS*, **204**, 17
- Werk, J. K., Prochaska, J. X., Tumlinson, J., et al. 2014, *ApJ*, **792**, 8
- White, S. D. M., & Rees, M. J. 1978, *MNRAS*, **183**, 341
- Wiersma, R. P. C., Schaye, J., & Smith, B. D. 2009a, *MNRAS*, **393**, 99
- Wiersma, R. P. C., Schaye, J., Theuns, T., Dalla Vecchia, C., & Tornatore, L. 2009b, *MNRAS*, **399**, 574
- Zwaan, M. A., van der Hulst, J. M., Briggs, F. H., Verheijen, M. A. W., & Ryan-Weber, E. V. 2005, *MNRAS*, **364**, 1467
- Zhu, G., & Ménard, B. 2013, *ApJ*, **770**, 130

Appendix A: Supplementary tables and figures**Table A.1.** COS QSO sample.

No.	QSO (COS name)	QSO (NED name)	α_{2000}	δ_{2000}	z_{QSO}	Δz_{abs}
1	1ES1028+511	2MASX J10311847+5053358	157.83	50.89	0.360	0.095
2	1ES1553+113	[HB89] 1553+113	238.93	11.19	0.360	0.098
3	1H-2129-624	2MASX J21362313-6224008	324.10	-62.40	0.059	0.041
4	1SAXJ1032.3+5051	2MASSi J1032161+505120	158.07	50.86	0.173	0.098
5	2DFGRSS393Z082	GALEXASC J024500.80-300722.3	41.25	-30.12	0.339	0.098
6	2DFGRSS394Z150 ^a	GALEXASC J024613.27-302942.2	41.56	-30.50	0.131	0.075
7	2E-1058.1+1102	[HB89] 1058+110	165.20	10.77	0.423	0.098
8	2MASS-J09311671+2628474	SDSS J093116.70+262847.4	142.82	26.48	0.781	0.088
9	2MASS-J09512393+3542490	2MASSi J0951239+354248	147.85	35.71	0.399	0
10	2MASS-J09591486+3203573	SDSS J095914.84+320357.2	149.81	32.07	0.565	0.098

Notes. The full version of Table A.1 is only available in electronic form at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](ftp://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/>. ^(a) Spectrum shows no QSO characteristics; possibly wrong source (white dwarf) observed; not considered in study.

Table A.2. Absorption-line systems.

No.	QSO (COS name)	z_{abs}	Ion	W_r^a [mÅ]	ΔW_r [mÅ]	$\log N$	$\Delta(\log N)$
1	2DFGRSS393Z082	0.004	H I	563	29		
2			Si II	33	12	12.49	0.25
3			Si III	69	27	12.91	0.15
4			Si IV	<20		<12.68	
5			C II	53	18	13.53	0.23
6			C IV				
7	2MASS-J10512569+1247462	0.003	H I	1027	103		
8			Si II				
9			Si III	190	32	13.13	0.12
10			Si IV	88	26	13.17	0.15
11			C II	101	22	13.83	0.15
12			C IV				

Notes. The full version of Table A.2 is only available in electronic form at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](ftp://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/>. ^(a) Used transitions: H I λ 1215, Si II λ 1260, Si III λ 1206, Si IV λ 1393, C II λ 1334, and C IV λ 1548.

Table A.3. Si III candidate systems.

No.	QSO (COS name)	z_{abs}
1	2MASS-J10131797+0500342	0.046
2	4C-01.61	0.038
3	IRAS01003-2238	0.040
4	MRK1513	0.028
5	PG1112+431	0.018
6	PG1202+281	0.051
7	PHL1811	0.012
8	RXJ0439.6-5311	0.057
9	SDSSJ014143.20+134032.0	0.003
10	SDSSJ024250.85-075914.2	0.005
11	SDSSJ040148.98-054056.5	0.029
12	SDSSJ094331.61+053131.4	0.086
13	SDSSJ101622.60+470643.3	0.057
14	SDSSJ102218.99+013218.8	0.067
15	SDSSJ122018.43+064119.6	0.086
16	SDSSJ150455.56+564920.3	0.036
17	SDSSJ155048.29+400144.9	0.077
18	SDSSJ155304.92+354828.6	0.028
19	SDSSJ161649.42+415416.3	0.089
20	VV2006-J015953.0+134554	0.004

Notes. Detected only in Si III and H I Ly α , but not confirmed in other metal lines.

Table A.4. Comparison with (revised) Danforth et al. (2016) absorber list.

QSO (COS name)	z_{abs}	Comment
Danforth detections without Richter counterpart		
3C57	0.077417	many line blends
3C57	0.089742	candidate metal lines are offset from Ly α
MR2251-178	0.010725	candidate metal lines are offset from Ly α
RXJ1230.8+0115	0.071728	no evidence for metal absorption
Richter candidate system without Danforth counterpart		
RXJ0439.6-5311	0.057400	possible Si III absorber present, but blend with intrinsic Ly β

Fig. A.1. Velocity profiles.

Fig. A.1. continued.

Fig. A.1. continued.

Fig. A.1. continued.

Fig. A.1. continued.

Fig. A.1. continued.

Fig. A.1. continued.