An HST/COS legacy survey of intervening Si\(\text{\textsc{iii}}\) absorption in the extended gaseous halos of low-redshift galaxies\(^*\),\(^{**}\)

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ABSTRACT

**Aims.** Doubly ionized silicon (Si\(\text{\textsc{iii}}\)) 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\(\text{\textsc{iii}}\)-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\(\text{\textsc{iii}}\) absorption statistics with predictions provided by the model. We also compared redshifts and positions of the absorbers with those of ~64,000 galaxies using archival galaxy-survey data to investigate the relation between intervening Si\(\text{\textsc{iii}}\) absorbers and the CGM.

**Results.** Along a total redshift path of \(\Delta z = 5\), we identify 69 intervening Si\(\text{\textsc{iii}}\) systems that all show associated absorption from other low and high ions (e.g., H\(\text{\textsc{i}}\), Si\(\text{\textsc{ii}}\), Si\(\text{\textsc{iv}}\), C\(\text{\textsc{ii}}\), C\(\text{\textsc{iv}}\)). We derive a bias-corrected number density of \(dN/dz(\text{Si}\text{\textsc{iii}}) = 2.5 \pm 0.4\) for absorbers with column densities \(\log N(\text{Si}\text{\textsc{iii}}) > 12.2\), which is ~3 times the number density of strong Mg\(\text{\textsc{ii}}\) systems at \(z = 0\). This number density matches the expected cross section of a Si\(\text{\textsc{iii}}\) absorbing CGM around the local galaxy population with a mean covering fraction of \(f(\rho) = 0.69\). For the majority (~60 percent) of the absorbers, we identify possible host galaxies within 300 \(\text{km} \, \text{s}^{-1}\) of the absorbers and derive impact parameters \(\rho < 200 \text{ kpc}\), demonstrating that the spatial distributions of Si\(\text{\textsc{iii}}\) absorbers and galaxies are highly correlated.

**Conclusions.** Our study indicates that the majority of Si\(\text{\textsc{iii}}\)-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\(\text{\textsc{iii}}\), 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-Escude 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
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; Tomlinson 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 II 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 12106). This is because of the very high oscillator strength of Si III 12106 of \( f = 1.63 \) (Morton 2003) and the relatively large cosmic abundance of silicon (log \( \text{[Si/H]} \) = \(-4.49\); 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 12106 transition for the study of the CGM we show in Fig. 1 the expected fractional abundance of the Si ions Si II–Si VII 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 \( n_H = -2.0 \) 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 12106 absorption in the low-redshift Universe is expected to be detectable (if not blended by other spectral features) in basically all damped Lyman \( \alpha \) absorbers (DLAs; log \( N(HI) \geq 20.3 \)), sub-damped Lyman \( \alpha \) absorbers (sub-DLAs; \( 19.0 \leq \log N(HI) < 20.3 \)), Lyman-limit systems (LLS; \( 17.2 \leq \log N(HI) < 19.0 \)), 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 \( N(HI) < 17.2 \)), where the minimum H I column density to detect Si III with HST/COS in solar-metallicity gas at moderate gas densities (\( n_H \sim 10^{-3} \) cm\(^{-3}\)) can be as low as log \( N(HI) = 14 \) (see Sect. 7.1).

Low ion lines with 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 \( N(HI) \)), while high ion such as C IV and O VI predominately trace highly-ionized gas at gas densities that are typically below \( n_H \sim 10^{-2} \) 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
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 H1 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 \( z \lesssim 0.1 \). 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 \( \text{III} \) absorption at \( z \leq 0.1 \) in each spectrum. We generally exclude the velocity range between \( v_{\text{abs}} = 0\text{–}500 \text{ km s}^{-1} \) where absorption by local disk gas and by intermediate- and high-redshift 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 \( z_{\text{QSO}} \). 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 \( \text{III} \) absorption (see Table A.1, last column).

For the determination of the Si \( \text{III} \) number density (Sect. 4.2) we further need to consider the detection limit for Si \( \text{III} \) absorption along each sightline, which depends on the \( S/N \) in the relevant part of the spectrum where intervening Si \( \text{III} \) absorption is expected to occur. The minimum column density, \( N_{\text{lim}} \), that can be detected at 3\( \sigma \) significance from an unresolved absorption line with a laboratory wavelength \( \lambda_0 \) 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):

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

For the only available Si \( \text{III} \) transition in the UV range we have \( \lambda_0 = 1206.500 \text{ Å} \) and \( f = 1.62732 \) (Morton 2003), so that for a \( S/N \) of 4 per resolution element the formal 3\( \sigma \) detection limit
for $R = 15000$ 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 $\geq 12$, 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 step, we let an automated line-finder algorithm identify absorption features whose wavelengths would correspond to combined

\[ H_0 = 69.7 \text{ km s}^{-1} \text{Mpc}^{-1} \] (Hinshaw et al. 2013)\(^2\). 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, $p$, of the galaxies to the LOS. There are 11 127 galaxies within $p = 1$ 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 $\phi$ 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 SDSS J141542.90+163413.8 and UKS J0242-724 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.

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 archive\(^1\). 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 $\Lambda$CDM cosmology with $\Omega_{\Lambda} = 0.72, \Omega_m = 0.28$ and $H_0 = 69.7 \text{ km s}^{-1} \text{Mpc}^{-1}$ (Hinshaw et al. 2013)\(^2\).

\(^{1}\) http://simbad.u-strasbg.fr

\(^{2}\) These values are consistent at the 2$\sigma$ level with the latest measured values by the Planck Collaboration (Planck Collaboration XIII 2015).
Fig. 2. Five examples for velocity profiles of Si$\text{iii}$-selected absorption line systems in our HST/COS survey with decreasing Si$\text{iii}$ $\lambda 1206$ absorption strengths (gray-shaded area; from left to right). Shown are the velocity profiles of H$\text{i}$, Si$\text{iii}$, Si$\text{ii}$, Si$\text{iv}$, C$\text{ii}$, and C$\text{iv}$ (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$\text{iii}$ 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$\text{iii}$ 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$\text{iii}$ $\lambda 1206$ 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$\text{iii}$ 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 $N$(Si$\text{iii}$) for absorbers where the Si$\text{iii}$ $\lambda 1206$ 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 $N_{\text{lim}}$(Si$\text{iii}$) for each sightline (see Eq. (1)) follows that more than 90 percent of all sightlines are sensitive to detect Si$\text{iii}$ absorbers with log $N$(Si$\text{iii}$) < 12.2, but only four such systems are found in our data (fractional abundance 4/69 $\approx 0.04$). Therefore, intervening Si$\text{iii}$ absorbers with log $N$(Si$\text{iii}$) < 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 $N$(Si$\text{iii}$) = 14. Even if some of the saturated absorbers (gray-shaded range) would have logarithmic Si$\text{iii}$ column densities > 14, their number would be small compared to absorbers with log $N$(Si$\text{iii}$) < 14. Our conclusion is that the characteristic column density range for intervening Si$\text{iii}$ absorbers is log $N$(Si$\text{iii}$) = 12.2−14.0.
4.2. Number density of Si\textsc{iii} absorbers

For the determination of the number density of intervening Si\textsc{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, $\log N_{\text{lim}}(\text{Si\textsc{iii}}) \geq 12.2$ represents the column density range that is characteristic for intervening Si\textsc{iii} absorbers. 63 Si\textsc{iii} absorbers in our sample have column densities $\log N_{\text{lim}}(\text{Si\textsc{iii}}) \geq 12.2$ 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 $\log N_{\text{lim}}(\text{Si\textsc{iii}}) = 11.8$ we derive $dN/dz = 4.0 \pm 0.7$ (31 absorbers, $\Delta z_{\text{abs,tot}} = 7.8$), while for $\log N_{\text{lim}}(\text{Si\textsc{iii}}) = 12.6$ 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 $\log N(\text{Si\textsc{iii}}) \approx 11.8$--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\textsc{i} Ly$\alpha$ as well as Ly$\beta$.

We have scanned the various original COS proposals that outline the motivation for observing the LOS along which we detect intervening Si\textsc{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 $dN/dz(\text{Si\textsc{iii}})$ 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\textsc{iii} absorbers for the different limiting Si\textsc{iii} column densities: $dN/dz = 3.8 \pm 0.7$ for $\log N_{\text{lim}}(\text{Si\textsc{iii}}) = 11.8$, $dN/dz = 2.5 \pm 0.4$ for $\log N_{\text{lim}}(\text{Si\textsc{iii}}) = 12.2$, and $dN/dz = 1.7 \pm 0.3$ for $\log N_{\text{lim}}(\text{Si\textsc{iii}}) = 12.6$. For the range $\log N(\text{Si\textsc{iii}}) = 11.8$--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\textsc{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\textsc{iii} absorbers per unit redshift in our survey, $dN/dz$, for the three different limiting Si\textsc{iii} column densities, $\log N_{\text{lim}}(\text{Si\textsc{iii}}) = 11.8$, 12.2 (dashed red line), and 12.6. In the following, we refer to these values when discussing the number densities of intervening Si\textsc{iii} absorbers.

4.3. Associated absorption from other ions

4.3.1. H\textsc{i}

As outlined in the introduction, the Si\textsc{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\textsc{i} column density in the Si\textsc{iii} absorbing gas varies over several orders of magnitudes, ranging from $\log N(\text{H\textsc{i}}) \sim 14$ up to $\log N(\text{H\textsc{i}}) \sim 22$, 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\textsc{iii} absorbers are presented in Sect. 7. In the left panel of Fig. 6 we show the distribution of H\textsc{i} Ly$\alpha$ equivalent widths in the Si\textsc{iii}-selected absorbers, which similarly span an extremely large range from $W_e \approx 250$ mÅ to $W_e \approx 5$ Å. We generally refrain from estimating the H\textsc{i} column densities from the saturated H\textsc{i} Ly$\alpha$ lines because of the very large uncertainties that such an estimate would be afflicted with.
Figure 5. Number densities, $dN/dz$, of intervening Si\textsc{iii} absorbers for different limiting column densities.

It is worth noting that our absorber sample contains four damped Ly\alpha/sub-damped Ly\alpha systems (DLAs/sub-DLAs) with log $N$(H\textsc{i}) > 19.2, as estimated from fitting the damping wings of the Ly\alpha 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 $dN/dz = 0.2$. 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 H\textsc{i} mass function of $z \approx 0$ galaxies (Zwaan et al. 2005).

4.3.2. Si\textsc{ii}

Detailed ionization models (see Sect. 7) indicate that regions with gas densities log $n_g \geq -3.5$ and sufficiently large neutral hydrogen column densities are expected to show both Si\textsc{iii} as well as Si\textsc{ii} absorption. Because Si\textsc{ii} and Mg\textsc{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\textsc{ii} can be directly compared with the well-established statistics on intervening Mg\textsc{ii} absorbers. The presence of Si\textsc{ii} absorption without associated Si\textsc{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\textsc{iii}-selected is not expected to introduce a selection bias in our Si\textsc{ii} statistics.

Fourty of our Si\textsc{iii} absorbers show associated Si\textsc{ii} absorption in the strongest of the available Si\textsc{iii} lines at $\lambda_0 = 1260.42$ Å. The equivalent-width distribution for Si\textsc{ii} $\lambda1260$ in these absorbers is shown in the middle panel of Fig. 6. It shows that the majority (80 percent) of the detected Si\textsc{ii} lines have equivalent widths in the $\lambda1260$ line of <300 mÅ. To compare the observed number density of Si\textsc{ii}-bearing absorbers with that of the prominent strong Mg\textsc{ii} systems, i.e., systems that have an equivalent width of $W_r \geq 300$ mÅ in the Mg\textsc{ii} $\lambda2976$ line, we need to convert the observed Si\textsc{ii} $\lambda1260$ equivalent widths into Mg\textsc{ii} $\lambda2976$ equivalent widths. For this we use the Si\textsc{ii}/Mg\textsc{ii} conversion scheme presented in Herenz et al. (2013), after which an equivalent width of $W_r = 300$ mÅ in the Mg\textsc{ii} $\lambda2976$ line corresponds to an equivalent width of $W_r = 140$ mÅ in Si\textsc{ii} $\lambda1260$, assuming solar relative abundances of Mg and Si. In our absorber sample we have 22 systems that have $W_r \geq 140$ mÅ in the Si\textsc{ii} $\lambda1260$ line, from which we indirectly infer a number density of strong Mg\textsc{ii} absorbers at $z \leq 0.1$ of $dN/dz \approx 1.0$. This value is in good agreement with the expectations for $dN/dz$(Mg\textsc{ii} $\lambda2976$) based on the redshift evolution of strong Mg\textsc{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\textsc{iv}

There are 38 Si\textsc{iv} absorbers in our sample that show associated Si\textsc{iv} absorption (the two available Si\textsc{iv} transitions are located at $\lambda_0 = 1393.8$ and 1402.8 Å, the former being the stronger of the two transitions; Morton 2003). The distribution of Si\textsc{iv} $\lambda1393$ equivalent widths of the 38 absorbers detected in Si\textsc{iv} is shown in the right panel of Fig. 6. Similarly as for Si\textsc{ii}, the majority of the Si\textsc{iv} $\lambda1393$ equivalent widths are small (82 percent have $W_r(1393) < 300$ mÅ). From the observed frequency of Si\textsc{iv} absorption in the Si\textsc{iii}-selected systems we estimate $dN/dz(Si\textsc{iv}) \geq 1.5$ for log $N$(Si\textsc{iv}) $\geq 12.6$. The occurrence of Si\textsc{iv} absorption without associated Si\textsc{iii} absorption in the CGM/IGM is possible, in principle, but is relevant only for absorbers at relatively low gas densities (log $n_g \leq -4.2$; see Sect. 7). Still, we formally can only give a lower limit for $dN/dz(Si\textsc{iv})$ from our study.

4.4. Correlation plots

In Fig. 7 we show correlations between the measured (logarithmic) equivalent widths of Si\textsc{iii} $\lambda1260$, H\textsc{i} $\lambda$ Ly\alpha, Si\textsc{ii} $\lambda1260$, and Si\textsc{iv} $\lambda1393$ for absorbers in which the absorption in these ions is aligned in velocity space within one COS resolution element (20 km s\textsuperscript{-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\textsc{iii} vs. H\textsc{i}

For log [$W_r(\lambda\text{Ly}\alpha)] \leq 3$ the Si\textsc{iii} $\lambda1260$ equivalent width rises steeply with the mildly increasing equivalent width of the fully saturated H\textsc{i} Ly\alpha absorption (Fig. 7; left panel). This trend indicates (as expected) that Si\textsc{iii} and H\textsc{i} trace the same physical regions that span a large range in neutral (and total) gas column densities. For log [$W_r(\lambda\text{Ly}\alpha)] > 3$ the correlation turns over into a somewhat flatter regime because the Si\textsc{iii} $\lambda1260$ absorption itself becomes saturated at such high total gas columns.

4.4.2. Si\textsc{iii} vs. Si\textsc{ii}

The equivalent widths of Si\textsc{iii} $\lambda1260$ and Si\textsc{ii} $\lambda1260$ 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\textsc{iii} arises in the same gas phase as Si\textsc{ii}, i.e., in predominantly neutral and/or mildly ionized gas. Some of the systems with upper limits in $W_r(\lambda1260)$ (open circles/arrows) have relatively strong Si\textsc{iii} absorption without a Si\textsc{ii} counterpart, implying that these absorbers consist of predominantly ionized gas that is traced by higher ions (e.g., Si\textsc{iv}, see below).

4.4.3. Si\textsc{iii} vs. Si\textsc{iv}

For systems that show both Si\textsc{iii} as well as Si\textsc{iv} absorption the equivalent width of Si\textsc{iii} $\lambda1260$ is also correlated with that of
Si IV λ1393, 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 λ1260 against that of Si IV λ1393 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 λ1206, H I Ly α, Si II λ1260, and Si IV λ1393 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, \( \phi \), 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:

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

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
University 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., Kapczkiz 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 SiIII 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 α = −1.10 and ϕ⋆ = 1.25 × 10^−2 h^3 Mpc^−3 for h = 1.0. We transform these parameters to the cosmological frame defined in Sect. 3.3. and calculate ϕ = ϕ⋆ Γ(α + 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 ≥ 0.001 L⋆ contain metal-absorbing gas within their virial radii (Rvir). We initially assume a unity covering fraction of the absorbing gas, so that the effective absorption cross section is simply πR^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 Rvir 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 Rvir 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 ϕ(L) and an effective absorption cross section A(L) = π R^2. We thus have C = log (L/ 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 − Rvir-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 ϕ(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, ⟨f_c⟩ = 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 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⋆ ≥ 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⋆ ≥ 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 ⟨f_c⟩ = 0.1–0.9 this absorber number density is remarkably close to the observed number density of intervening SiIII 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 a in each row the normalization density from ϕ_{min}^* over ϕ_{pref}^* to ϕ_{max}^* (where

\begin{align*}
\text{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.}
\end{align*}
in the range $\rho > \rho_{vir}$, the absorption rate decreases rapidly with increasing impact parameter because the fraction of sightlines that pass galaxies at $\rho > R_{vir}$ increases. Figure 9 can be directly compared to the observed absorption rate around low-redshift galaxies, as 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, $\langle F_{eff}(r_{max}) \rangle$, 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 $\Delta r$ and radius $r$ is $\Delta r \times 2\pi r$, the absorption rates need to be weighted with $1/\pi r^{2}$ to obtain $\langle F_{eff}(r_{max}) \rangle$. 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...
To characterize the true absorber-galaxy connection at high redshift, we would like to emphasize that the impact parameters of the nearest galaxy to the LOS in the absorber samples are, on average, substantially smaller than those in the control samples. Such a trend is indeed seen in our data: for 76 percent of the LOS that exhibit an intervening Si \( \text{\textsc{iii}} \) absorber, the galaxy with the smallest impact parameter is located within 1000 km s\(^{-1}\) of the absorption redshift.

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 high redshift absorbers.
Si\textsc{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 \( \langle F_c(r_{\text{max}}) \rangle = 0.08 \) for \( r_{\text{max}} = 400 \) kpc and \( \langle F_c(r_{\text{max}}) \rangle = 0.01 \) for \( r_{\text{max}} = 1000 \) kpc. These effective covering fractions are comparable to those expected for a population of \( L > 0.1L^\star \) galaxies that are surrounded by a CGM that reaches out to \( R_{\text{vir}} \) 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\textsc{iii} \( \lambda 1206 \) versus the impact parameters of the galaxies nearest to the absorbers. For \( \rho < 200 \) kpc the equivalent width scatter 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 mÅ for \( \rho > 500 \) 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 \( \rho \) (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\textsc{ii} absorbers it is known that the mean Mg\textsc{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\textsc{iii}, the large scatter for \( W_r(\text{Si}\textsc{iii} \lambda 1206) \) at \( \rho < 200 \) 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 \( \rho \) then simply reflects the decreasing likelihood to miss luminous galaxies around the absorbers that are responsible for the strongest absorbers. For large values of \( \rho \), 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...
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., $U = n_\gamma / n_T$). For an assumed ionizing radiation field one can calculate $n_\gamma$ and thus can relate $U$ with the gas density $n_T$.

In Figure 13 we have plotted (as an example) the expected H II, Si II, Si III, and Si IV column densities against $n_T$ 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 $n_T$ 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 ($log n_T < -3.5$), while Si III dominates in the density range $-3.5 < log n_T < -2.0$. Si II is dominant at $log n_T > -2.0$, 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:

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

In Fig. 14 we have plotted the observed column-density ratios of these ions (and relevant limits) together with predictions from
as a function of the gas density (log \(n_{\text{iii}}\)) for the Si\(\text{II}\) elements. The gray-shaded area indicates the density that is typical for the Si\(\text{III}/\text{Si}\text{IV}\) 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\(\text{II}, \text{Si}\text{III}, \text{Si}\text{IV}, \text{and Mg}\text{II}\) (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\(\text{II}\) and/or Si\(\text{IV}\) column densities are too high for the observed Si\(\text{III}\) 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\(\text{III}/\text{Si}\text{IV}\) and Si\(\text{III}/\text{Si}\text{II}\) 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\(\text{II}\) and Si\(\text{IV}\) 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 be 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\(\text{III}\) absorption arises in both a diffuse ionized gas phase traced by Si\(\text{IV}/\text{Si}\text{III}\) as well as a somewhat denser (partly neutral) gas phase traced by Si\(\text{II}/\text{Si}\text{III}\). To further investigate the characteristic densities of these two phases we have plotted in Fig. 15 the column densities log \(N(\text{Si}\text{III})\) vs. log \(N(\text{Si}\text{IV})\) (upper panel) and log \(N(\text{Si}\text{III})\) vs. log \(N(\text{Si}\text{II})\) (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 \(N(\text{Si}\text{III})\) have to be regarded as an upper limit for the Si\(\text{III}\) column in each phase.

For the absorbers that are detected simultaneously in Si\(\text{III}\) and Si\(\text{IV}\) (upper panel of Fig. 15, filled circles) the data points scatter within ~0.7 dex around the \(N(\text{Si}\text{III}) = N(\text{Si}\text{IV})\) line. For the absorbers that are detected simultaneously in Si\(\text{III}\) and Si\(\text{II}\) (lower panel of Fig. 15, filled circles) the measured Si\(\text{II}\) column densities are typically lower than that of Si\(\text{III}\), but (again) note that a considerable fraction of the Si\(\text{III}\) column may arise in the Si\(\text{IV}\) phase, so that log \(N(\text{Si}\text{III})/N(\text{Si}\text{IV})\) 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\(\text{II}/\text{Si}\text{III}/\text{Si}\text{IV}\) column densities. From the exploration of the parameter space the Cloudy models deliver, however, a characteristic gas density that separates the Si\(\text{IV}/\text{Si}\text{III}\) from the Si\(\text{II}/\text{Si}\text{III}\) phase in the absorbers (see also Fig. 13). We find that the Si\(\text{IV}/\text{Si}\text{III}\) phase traces gas with densities log \(n_H\) ≤ −3.0 (in Fig. 13 indicated with the gray-shaded area), while the Si\(\text{II}/\text{Si}\text{III}\) phase has higher densities in the range log \(n_H\) > −3.0.

### 7.4. Total gas mass and baryon budget

Our observations and Cloudy models imply that Si\(\text{III}\) 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\(\text{III}\) absorbers and the metal-enriched CGM. To derive the total gas mass of the Si\(\text{III}\) systems in our sample we need to calculate the amount of ionized hydrogen in each absorber. Because of the much higher
ionization fraction in the Si IV/Si III systems compared to the Si II/Si III phase we here concentrate on the estimate of $N$(H II) in low-density Si III absorbers that are associated with Si IV.

For the range $\log N$(H II) = 14–17 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:

$$\log N$(H II) $\approx \log N$(Si III) + $\log Y - \log (\text{Si/H})_o,$$

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 $N$(H II) in each Si IV/Si III absorber, from which the integrated (=total) column density, $N$(H II)_tot, can then be determined.

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

$$\Omega_0$(Si III) $\equiv \mu m_H H_0 \rho_c^{-1} N$(H II)_tot $\Delta X^{-1}$,

with $\mu = 1.3$, $m_H = 1.673 \times 10^{-27}$ kg, $H_0 = 69.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Hinshaw et al. 2013), and $\rho_c = 3H_0^2/8\pi G$. The comoving path length $\Delta X$ available for the detection of Si IV/Si III absorbers along each sightline is given by:

$$\Delta X \equiv (1+z)^2\left[\Omega_{\text{mat}}(1+z)^2 + \Omega_\Lambda\right]^{-1/2} \Delta X_{\text{abs}}.$$  

(8)

The integration over all sightlines then delivers $\Delta X_{\text{tot}}$. For our bias-corrected Si IV/Si III absorber sample with $\log N$(Si III) $\geq$ 12.2 we have $N$(H II)_tot $\geq 5.4 \times 10^{20} \text{ cm}^{-2}$ and $\Delta X_{\text{tot}} = 20.65$. The cosmological mass density can then be written as $\Omega_0$(Si III) $\geq 4.6 \times 10^{-4} Z_{\odot}$, where $Z_{\odot}$ is the Si abundance in the gas relative to the solar value, $\log (\text{Si/H})_\odot = -4.49$ (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 $z = 0$ ($\Omega_0$(H I) $= 4.7 \pm 0.7 \times 10^{-4}$; Zwaan et al. 2005).

On the one hand, $\Omega_0$(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 $Z_{\odot}$ = 0.5 as a conservative upper limit for the metallicity of the Si III absorbers in our survey. This value leads to $\Omega_0$(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 $\leq$ 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 $\langle f_X \rangle \approx 0.7$. While the distances and the
space distribution of Si $\text{III}$ 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 $\text{III}$ absorption out to $\sim 200$ 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 $\text{III}$ is ubiquitous in the extended CGM of low-redshift galaxies. The existence of such discrete Si $\text{III}$ 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 $\text{III}$ absorbers with $\log N($Si $\text{III})\geq 12.2$ and the derived impact parameter distribution are in line with a scenario, in which all Si $\text{III}$ 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 $\text{III}$ 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) $T = 10^3-10^6$ 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 ($T < 10^3$ K) gas patches embedded in such a medium that could give rise to intervening Si $\text{III}$/Si $\text{IV}$ absorption. Some of the galaxy/absorber pairs that have apparent impact parameters in the range $\rho = 200-1000$ kpc may belong to such group absorbers. The Cloudy modeling predicts that Si $\text{III}$/Si $\text{IV}$ absorbers trace gas down to thermal pressures of $P/k = n T \sim 1$ cm$^{-3}$ 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 $P/k$ would also 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 $\text{III}$ absorbers breaks down for column densities $\log N($Si $\text{III})\leq 12.2$ (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 $\text{III}$ absorbers with $\log N($Si $\text{III}) \leq 12.2$ is also $\sim 10$ times less than the number density of absorbers with $\log N($Si $\text{III}) \geq 12.2$, supporting a scenario in which high-column density Si $\text{III}$ systems trace the CGM of galaxies, while low-column density Si $\text{III}$ 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 $\text{III}$ 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 $z = 0.0337$ Si $\text{III}$ 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. 1999) at impact parameters $\rho < 220$ kpc. In principle, the observed Si $\text{III}$ absorption at $z = 0.0337$ could be an absorber pair that consists 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 $\alpha$ absorption together with the Cloudy model of the Si $\text{III}$/Si $\text{IV}$ 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 $\text{III}$ 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 $\text{III}$ absorption-line studies

We are not aware of any other systematic studies in the literature that focus explicitly on Si $\text{III}$-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 $\text{III}$ and other intermediate ions (e.g., C $\text{III}$) 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 $\text{III}$ absorbers of $dN/dz = 7.4_{-1.2}^{+1.1}$ for $\log N($Si $\text{III}) > 12.2$ for this redshift range, based on a total redshift path of $\Delta z = 5.2$. This value is slightly higher than 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 $dN/dz = 5.9_{-0.6}^{+0.7}$ for $\log N($Si $\text{III}) > 12.2$. Moreover, their study suggests an increase for $dN/dz($Si $\text{III}$) 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 $dN/dz($Si $\text{III}$) derived by Danforth et al. (2016) stems from the less stringent selection criteria for
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 $dN/dz$(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 $N$(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 $0.60^{+0.15}_{-0.13}$ within $0.54R_{\text{halo}}$ and $0.14^{+0.11}_{-0.05}$ for the range $0.54-1.02R_{\text{halo}}$, but no significant Si III absorption beyond. These covering fractions are lower than our estimate of $(f_c) = 0.69 \pm 0.11$. This is not surprising, however, since their study considers only strong Si III systems with $W_r > 100 \text{ mÅ}$ (log $N$(Si III) > 12.6), while our estimate is based on a more sensitive search including weak and strong absorbers with log $N$(Si III) > 12.2. If we adopt our measured value of $dN/dz$(Si III) = 1.9 for N(Si III) ≥ 12.6 for our estimate of $(f_c)$ using Eq. (4), we obtain a value of $0.47^{+0.09}_{-0.08}$ within $R_{\text{vir}}$, thus in good agreement with the Liang & Chen (2014) estimate. Also Werk et al. (2013) consider only strong Si III absorbers around $L \approx L^*$ with $W_r > 100 \text{ mÅ}$, and find $(f_c) = 0.72^{+0.07}_{-0.17}$ 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 $(f_c)$ (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 $0.5R_{\text{vir}}$. 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 $N$(Si III) > 12.2 at the redshifts of the dwarf galaxies $(f_c) = 0.43^{+0.10}_{-0.11}$, demonstrating that the absorption fraction of the warm CGM traced by Si III around dwarf galaxies is only $\sim 60$ 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 $R_{\text{vir}}$ 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(O VI) ≈ 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 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; Pepper-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 II 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(Si III) of ∼6 for log N(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(Si III) ≈ 3), the Si III number density derived by us is in very good agreement with the results by Smith et al. with the works 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 × 10⁶ h⁻³ Mₜ₀ (DM) and 8.7 × 10⁶ h⁻¹ Mₜ₀ (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(Si III) > 12.2 (log [W_L(1206)/mA] > 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 ≈ 15 000–20 000 K and a density of n_H ≈ 10⁴–10⁵ 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 ≈ 2–160 cm⁻³ 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 ≤ 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 ≤ 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 = 0.00014–0.9789 along a total redshift path of Δz ≈ 24. The restframe equivalent widths in the Si III λ1206 line lie in the range W_r = 13–885 mA, corresponding to Si III column densities log N(Si III) > 11.9. We derive a bias-corrected number density of intervening Si III systems of
We geometrically model the absorption cross section of Si\textsc{iii} absorption from other low and/or high ions. The positive impact parameters of Si\textsc{iii} absorbers, which indicate that Si\textsc{iii} absorption is typically accompanied by doubly ionized Si, contains substantially more baryonic matter than their neutral ISM.

(3) We geometrically model the absorption cross section of diffuse gas within the virial radii ($R_{\text{vir}}$) 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 $R_{\text{vir}}$ 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-Dorta et al. 2009), we obtain $dN/dz = 3.6 (f_c)$ as expected number density for CGM absorbers from $L > 0.001 L^*$ galaxies. In light of this result, the measured value of $dN/dz (\text{Si}\text{iii}) = 2.5 \pm 0.4$ is in line with the idea, that the majority of the intervening Si\textsc{iii} absorbers with log $N$(Si\textsc{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 $\langle f_c \rangle = 2.5/3.6 = 0.69$, 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\textsc{vi} absorbers) must partially arise from gas outside of the virial radius of galaxies.

(4) We compare the Si\textsc{iii} absorber redshifts and positions with that of ~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 $\rho < 200$ kpc, indicating that the spatial distributions of Si\textsc{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\textsc{iii} absorption and find no clustering of the galaxies, as expected. The observed Si\textsc{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\textsc{iii} absorbers.

(5) We estimate the baryon content of the Si\textsc{iii}-absorbing gas phase in the CGM at low $z$ using Cloudy ionization models. Assuming that the metallicity of the gas is $\leq 0.5$ solar, the cosmological mass density of the gas in Si\textsc{iii} absorbers is $\Omega_0 h (\text{Si}\text{iii}) \geq 9.2 \times 10^{-4}$. This lower limit is roughly twice the value derived for the H\textsc{i} 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\textsc{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\textsc{iii} absorbers with log $N$(Si\textsc{iii}) $\geq$ 12.2 typically arise within the extended halos of galaxies within $R_{\text{vir}}$, while weak systems with log $N$(Si\textsc{iii}) $< 12.2$ possibly also trace gas at larger distances (e.g., group environments or the IGMM). 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\textsc{iii} absorbers.

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Appendix A: Supplementary tables and figures

Table A.1. COS QSO sample.

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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 (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.

<table>
<thead>
<tr>
<th>No.</th>
<th>QSO (COS name)</th>
<th>z_{abs}</th>
<th>Ion</th>
<th>W_r [mÅ]</th>
<th>ΔW_r [mÅ]</th>
<th>log N</th>
<th>Δ(log N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2DFGRSS393Z082</td>
<td>0.004</td>
<td>H I</td>
<td>563</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>Si II</td>
<td>33</td>
<td>12</td>
<td>12.49</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>Si III</td>
<td>69</td>
<td>27</td>
<td>12.91</td>
<td>0.15</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>Si IV</td>
<td>&lt;20</td>
<td>&lt;12.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>C II</td>
<td>53</td>
<td>18</td>
<td>13.53</td>
<td>0.23</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>C IV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2MASS-J10512569+1247462</td>
<td>0.003</td>
<td>H I</td>
<td>1027</td>
<td>103</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>Si II</td>
<td>190</td>
<td>32</td>
<td>13.13</td>
<td>0.15</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>Si III</td>
<td>88</td>
<td>26</td>
<td>13.17</td>
<td>0.15</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>Si IV</td>
<td>101</td>
<td>22</td>
<td>13.83</td>
<td>0.15</td>
</tr>
</tbody>
</table>

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 (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/. (^a) Used transitions: H I λ1215, Si II λ1260, Si III λ1206, Si IV λ1393, C II λ1334, and C IV λ1548.
Table A.3. Si\textsc{iii} candidate systems.

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

Notes. Detected only in Si\textsc{iii} and H\textsc{i} Ly$\alpha$, but not confirmed in other metal lines.

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

<table>
<thead>
<tr>
<th>QSO (COS name)</th>
<th>$z_{\text{abs}}$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Danforth detections without Richter counterpart</td>
</tr>
<tr>
<td>3C57</td>
<td>0.077417</td>
<td>many line blends</td>
</tr>
<tr>
<td>3C57</td>
<td>0.089742</td>
<td>candidate metal lines are offset from Ly$\alpha$</td>
</tr>
<tr>
<td>MR2251-178</td>
<td>0.010725</td>
<td>candidate metal lines are offset from Ly$\alpha$</td>
</tr>
<tr>
<td>RXJ1230.8+0115</td>
<td>0.071728</td>
<td>no evidence for metal absorption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Richter candidate system without Danforth counterpart</td>
</tr>
<tr>
<td>RXJ0439.6-5311</td>
<td>0.057400</td>
<td>possible Si\textsc{iii} absorber present, but blend with intrinsic Ly$\beta$</td>
</tr>
</tbody>
</table>
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.