The circumgalactic medium of high-redshift galaxies

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Accepted 2014 July 28. Received 2014 July 21; in original form 2014 June 4

ABSTRACT

We study the properties of the circumgalactic medium (CGM) of high-$z$ galaxies in the metal enrichment simulations presented in Pallottini et al. At $z = 4$, we find that the simulated CGM gas density profiles are self-similar, once scaled with the virial radius of the parent dark matter halo. We also find a simple analytical expression relating the neutral hydrogen equivalent width ($EW_{HI}$) of CGM absorbers as a function of the line-of-sight impact parameter ($b$). We test our predictions against mock spectra extracted from the simulations and show that the model reproduces the $EW_{HI}(b)$ profile extracted from the synthetic spectra analysis. When compared with available data, our CGM model nicely predicts the observed $EW_{HI}(b)$ in $z \lesssim 2$ galaxies, and supports the idea that the CGM profile does not evolve with redshift.

Key words: methods: numerical – galaxies: high-redshift – intergalactic medium – cosmology: theory.

1 INTRODUCTION

The circumgalactic medium (CGM) is the extended interface between the interstellar medium (ISM) of a galaxy and the surrounding intergalactic medium (IGM). This component plays a key role in galactic evolution as it represents a mass reservoir and a repository of the mechanical and radiative energy produced by stars. Due to its low density, the CGM can be almost uniquely traced by absorption line experiments towards background sources, typically quasars. The intervening CGM associated with a foreground galaxy then leaves a characteristic spectral feature. Provided that a sufficiently large sample of galaxies is available, it is then possible to statistically determine the equivalent width (EW) of a given absorption line as a function of the line-of-sight (l.o.s) impact parameter ($b$).

The CGM has been probed so far up to $z \sim 3$ using absorption lines of both H\emph{i} (e.g. Rudie et al. 2012, 2013; Pieri et al. 2014) and heavy elements (e.g. Steidel et al. 2010; Borthakur et al. 2013; Churchill et al. 2013; Nielsen, Churchill & Kacprzak 2013; Jia Liang & Chen 2014). These observations show that the CGM extends up to $b \simeq 10 r_{vir}$, where $r_{vir}$ is the virial radius of the parent dark matter (DM) halo. An anticorrelation between EW and $b$ is observed; moreover, the EW profiles appear to be self-similar once scaled with $r_{vir}$. Finally, Chen (2012) suggested that CGM absorption profiles show no signs of evolution from $z \simeq 2$ to $z \simeq 0$.

In the framework of a $\Lambda$ cold dark matter (CDM) cosmological model, the CGM properties can be derived from numerical simulations simultaneously accounting for both large-scale ($\simeq$ Mpc) structure and small-scale ($\simeq$ kpc) galactic feedback. While such a huge dynamical range makes a truly self-consistent simulation impossible, these difficulties can be overcome by following the unresolved physical scales with subgrid models.

Along these lines, some numerical studies have focused on testing CGM metal enrichment models (e.g. Barai et al. 2013; Crain et al. 2013; Shen et al. 2013); others have investigated the imprint of the last phases of reionization on the IGM (e.g. Finlator et al. 2013; Keating et al. 2014) or the ISM/CGM overdensity–metallicity ($\Delta - Z$) relation as a function of redshift (Pallottini et al. 2014, hereafter P14). Surprisingly, little attention has been devoted so far to understand the physics beneath the observed CGM profile self-similarity and redshift independence.

In this Letter, we show that the previously found $\Delta - Z$ relation naturally arises from self-similar nature of the CGM density/metallicity profiles. We use this result to derive an analytical expression for $EW_{HI}(b)$ which we then test against synthetic spectra extracted from the simulations and available observational data.

2 NUMERICAL SIMULATIONS

We adopt the simulations described in P14 which were obtained by using a customized version of the adaptive mesh refinement code RAMSES (Teyssier 2002). Starting from cosmological initial conditions generated at $z = 199$, we evolve a ($10$ Mpc $h^{-1}$)$^3$ volume until $z = 4$. The DM mass resolution is $6.67 \times 10^7 h^{-1} M_{\odot}$, and the adaptive baryon spatial resolution ranges from $19.53$ to $1.22 h^{-1}$ kpc.

We include subgrid prescriptions for star formation, accounting for supernova (thermal) feedback and implementing metal-dependent stellar yields and return fractions. Our simulation reproduces the observed cosmic star formation rate
The gas density profile can then be written in terms of the self-similar variable $x$ as a piecewise power law of index $\alpha$:

$$
\rho_{\text{pp}}(x)/\rho_{\text{vir}} = \Theta(x_{\text{IGM}} - x)x^{-\alpha} + \Theta(x - x_{\text{IGM}})x^\alpha,
$$

(1)

where $\rho_{\text{vir}}$ is the gas density evaluated at the virial radius, $\Theta$ is the Heaviside function and $x_{\text{IGM}}$ denotes the location where the density approaches a constant value typical of the IGM in the proximity of galactic systems. The best-fitting values for the parameters are $\alpha = 1.87 \pm 0.05$, $\rho_{\text{vir}}/\rho = 37.5 \pm 4.7$ and $x_{\text{IGM}} = 3.8 \pm 0.2$. From the fit, we also find the relation $(\rho_{\text{vir}}/\rho)x_{\text{IGM}} \lesssim 3$. In the upper panel of Fig. 1, $\Delta_{\text{pp}} = \rho_{\text{pp}}/\rho$ is shown by the black dashed line.

The metallicity (Fig. 1, lower panel) is essentially flat in the ISM and rapidly declines in the CGM; this result is independent from the selected environment. The trend is however not universal in the IGM, as expected from the results of P14, where we showed that $Z$ is only weakly correlated with $\Delta$ in the IGM. Environments associated with massive DM haloes ($M_h \gtrsim 10^{9.5} \, M_\odot$) show an enriched ($Z \approx 10^{-1.5} \, Z_\odot$) IGM up to $x \approx 10^{3.5}$. Instead, haloes with $M_h \lesssim 10^{8} \, M_\odot$, which contain small galaxy groups or even isolated galaxies, only manage to pollute the IGM within $x \lesssim 10$. This trend is discussed in detail in fig. 13 of P14.

Finally, galaxies hosted in haloes with masses lower than $10^{9.5} \, M_\odot$ only show up as satellites (P14). Their effect is perceivable in Fig. 1 as a local perturbation to the global $\Delta$ and $Z$ trends at $x \gtrsim 1$. The satellite positions resulting from our simulation are in broad agreement with the outcome of the numerical simulation by Khandai et al. (2014), who find a flat satellite distribution at $x \gtrsim 1$ for $M_h \sim 10^{10} \, M_\odot$ (see their fig. 10).

2.2 Modelling H I absorption

From the fit to the simulated density profile, $\rho_{\text{pp}}(x)$, we build a simple analytical model that describes the H I absorption properties ($N_{\text{HI}}$ and $E_{\text{HI}}$) of the CGM/IGM.

The H I column density along an l.o.s. is defined as $N_{\text{HI}} = \int n_{\text{HI}} dl$, where $n$ is the total hydrogen density and $x_{\text{HI}}$ is the H I fraction. Assuming spherical symmetry, we express $N_{\text{HI}}$ through the following relation:

$$
N_{\text{HI}}(b) = \frac{2}{m_{\text{HI}}} \int_{0}^{\max r_{\text{HI}}} \rho_{\text{pp};x_{\text{HI}}} \frac{r}{\sqrt{r^2 + b^2}} dr,
$$

(2)

where $\rho_{\text{pp}}$ is given in equation (1), $b$ is the impact parameter, $m_{\text{HI}}$ is hydrogen mass, $l_{\text{max}} = \sqrt{b^2 + (\Delta v/H)^2}$, $H = H(z)$ is the Hubble constant and $\Delta v$ is the velocity window sampled by observations. Assuming local photoionization equilibrium (e.g. Dayal, Ferrara & Gallerani 2008), the H I fraction can be written as $x_{\text{HI}} = (1 + \xi) - \sqrt{(1 + \xi)^2 - T}$, where $\xi = (\Gamma_{\text{HI}} m_{\text{HI}})/(2 \rho_{\text{vir}} \alpha_{rec})$, $\alpha_{rec}$ is the recombination rate and $\Gamma_{\text{HI}} = \Gamma_{\text{HI}}(z)$ is the UV background photoionization rate. Consistent with P14 simulations, we use the UV intensity from Haardt & Madau (2012).

The H I Ly$\alpha$ equivalent width can be expressed as follows:

$$
E_{\text{HI}}(b) = \frac{c}{v_0} \int_{0}^{\Delta v} (1 - \exp(-N_{\text{HI}} \sigma_0 \phi)) \, dv,
$$

(3)

where $c$ is the speed of light, $v_0$ is the frequency of the Ly$\alpha$ transition, $\phi = \phi(v - v_0)/\Delta v$, $\Delta v$ is the Voigt profile (e.g. Meiksin 2009), $\Delta v = (v_0/c)\sqrt{2K T/m_{\text{HI}}}$ is the thermal Doppler broadening and $\sigma_0 = n_e^2 f/m_e c$, where $f$ is the oscillator strength, $e$ and $m_e$ are the electron charge and mass, respectively. By combining equations (1)–(3), we obtain the trend of $E_{\text{HI}}$ with $b$, for different values of $r_{\text{vir}}$ and $T$. 

2Therefore, we will use interchangeably overdensity and distance definitions for the three phases.
The EW$_{HI}(b)$ dependence on $r_{vir}$, entering through the density dependence on $x = r/r_{vir}$, results in a stretching/compression of the density profile. The temperature $T$, entering in the expressions for $Q_{ion}$ and $\Delta \nu$, regulates both HI at $x \gg x_{IGM}$ and the slope of the EW$_{HI}$ profile for $x \lesssim x_{IGM}$. For increasing (decreasing) $T$ values, HI is shifted downwards (upwards) while the slope becomes steeper (shallower). It is worth noticing that we are assuming a single temperature value both for the IGM and CGM. Moreover, we are neglecting turbulence, which may affect the Doppler broadening of CGM absorbers (e.g. Iapichino, Viel & Borgani 2013). Therefore, $T$ must be regarded as an 'effective temperature'; to make it clear we will use $T_{eff}$ to indicate this quantity.

3 TESTING THE H I ABSORPTION MODEL

We are now ready to test our model both against simulated QSO absorption spectra and real data.

3.1 Synthetic H i absorption spectra

We compute mock QSO absorption spectra along several l.o.s. drawn through the simulated box. The technique adopted to compute the H i optical depth is detailed in Gallerani, Choudhury & Ferrara (2006). In order to reproduce the mean transmitted flux observed at $z = 4$ ($F_{\text{mean}} = 0.41$; Becker et al. 2013), the intensity of the UV ionizing background (Haardt & Madau 2012) assumed in the simulation is rescaled upwards by a factor of 6.6, resulting into a photoionization rate $\log(n_{HI}/s) = -12$. We also include observational artefacts in our simulated spectra, following Rudie et al. (2013), a work based on HIERES spectra. We smooth the synthetic spectra to a resolution $R = 45$ 000, add to each pixel a Gaussian random deviate, yielding a signal-to-noise ratio $S/N = 100$, and we finally rebin the simulated transmitted flux in channels of width 0.4 Å.

Among the l.o.s. extracted from the simulations, we select the ones passing through a specific galactic environment, defined by its central halo mass $M_c$ and its corresponding $r_{vir}$. The sample of l.o.s. considered encompasses a wide range of impact parameters, namely $10^{-1}$–$10^2 r_{vir}$.

3.2 Largest gap statistics

Along each l.o.s., we identify the CGM absorption feature with the largest spectral gap$^3$ found in the corresponding synthetic spectrum (Gallerani et al. 2008a,b). In order to check that largest gaps correctly identify CGM absorption features, we compute the $N_{HI}$ along their corresponding l.o.s. paths, for different $b$ values, and for a set of galactic environments characterized by $M_c/M_\odot = 10^{10.5}$, $10^{10}$, $10^{9.5}$ and $10^9$, that correspond at $z = 4$ to $r_{vir}/kpc = 21, 14, 9.6$ and 6.5, respectively.

The results from a sample of 3000 l.o.s. are shown in Fig. 2. Superimposed to the $N_{HI}$ profiles obtained from the synthetic spectra analysis are the average $N_{HI}$ values inferred from the P14 simulations$^4$.

3.3 Comparison with simulations

As a next step, we compute the EW$_{HI}$ of the absorption features identified through the largest gap statistics as a function of the $b$ parameters, for the galactic environments presented in Fig. 2. The results are shown in the left-hand panel of Fig. 3 through red diamonds, purple downwards triangles, green squares and blue circles for $M_c/M_\odot = 10^{10.5}$, $10^{10}$, $10^{9.5}$ and $10^9$, respectively. In the same figure, black circles and corresponding error bars represent mean and rms values obtained by averaging the EW$_{HI}$ profiles of the four different galactic environments into bins of width $\Delta b$ such that $\log(\Delta b/kpc) \simeq 0.5$. As expected (see equation 3), the EW$_{HI}$ profiles follow the $N_{HI}$ trend (Fig. 2), namely EW$_{HI}$ decreases with $b$.

Finally, we fit the averaged EW$_{HI}$ profile resulting from the synthetic spectra analysis through our analytical model, finding the following best-fitting parameters: $\log(T_{eff}/K) = 4.7 \pm 0.3$ and $r_{vir} = 16 \pm 2$ kpc. The inferred $T_{eff}$ value agrees with typical values of the CGM/IGM temperature (P14) and $r_{vir}$ is consistent with the average virial radius of the galactic environments considered, namely $r_{mean} = 13 \pm 6$ kpc. This result represents a solid consistency check of our model which allows us to repeat the same experiment on real data.

Figure 2. Neutral hydrogen column density ($N_{HI}$) as a function of the normalized impact parameter ($b/r_{vir}$) for a set of galactic environments with central halo mass $M_c$. The mean and the rms $N_{HI}$ values inferred from the absorption spectra are shown through solid black lines and coloured shaded regions, respectively. The solid orange lines represent the average $N_{HI}$ inferred from the simulation (see footnote 4), while the dashed black lines denote the $N_{HI}$ resulting from the analytical model (equation 2) calculated for $\log(T_{eff}/K) = 5$.

and the column density resulting from the analytical model (equation 2) calculated for $\log(T_{eff}/K) = 5$. Fig. 2 shows that the largest gap statistics properly identifies CGM absorption features in H i absorption spectra.

This technique is particularly promising for studying the CGM absorption properties for high-$z$ ($z > 4$) quasar spectra. At these redshifts, the maximum observed transmitted flux drops below 50 per cent in the Ly$\alpha$ forest (Songaila 2004). The resulting large uncertainties in the continuum determination may therefore hamper a proper Voigt profile analysis.

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$^3$ Spectral gaps are defined as contiguous regions of the spectrum having an optical depth $\tau > 2.5$ over rest-frame intervals $> 1$ Å (Croft 1998).

$^4$ For each l.o.s., $N_{HI} = \int n_{HI} dl$, where the integration limits correspond to the borders of the environment, which in turn depend on $Z_{th}$. Changing the metallicity threshold marginally affects the results: using $Z_{th} = 10^{-6} Z_\odot$ yields a variation of $bN_{HI} \lesssim 10^{34}$ cm$^{-2}$ for the inferred column density. The orange lines are obtained by averaging $N_{HI}$ over $\sim 10^3$ l.o.s.
Neutral hydrogen equivalent width (EW) supported by the lack of evolution of CGM profiles from BF 2010, 1074 kpc quoted by Jia Liang & Chen (2014) values.

3.4 Comparison with observations

In the right-hand panel of Fig. 3, we compare our model with observations. Blue circles are the EW$_{H_\text{I}}$ derived at $z = 0.01$ by Jia Liang & Chen (2014); black circles and corresponding error bars represent mean and rms values obtained by averaging the same observational data into bins $\sim 40$ kpc large.

For this comparison, the model is calculated with $\log(T_{\text{eff}}/K) = -13$, i.e. the value at $z = 0.01$ given by Haardt & Madau (2012). By fitting5 observations with our analytical model, we find $\log(T_{\text{eff}}/K) = 3.6 \pm 0.7$ and $r_{\text{vir}} = 52 \pm 22$ kpc. $T_{\text{eff}}$ provides only an indicative value for the average temperature of the CMG/IGM. Although $r_{\text{vir}}$ is consistent within 1.2σ with the mean virial radius $r_{\text{vir}} = 144 \pm 74$ kpc quoted by Jia Liang & Chen (2014), we note that our model favours smaller $r_{\text{vir}}$ values.

The dashed black line in the right-hand panel of Fig. 3 represents our best-fitting model, while the violet solid line shows the model from Chen et al. (1998, 2001, hereafter C-model). Both the C-model and our best fit are in agreement with Jia Liang & Chen (2014) observations up to $b/kpc \sim 10^5$, i.e. in the CGM range ($b \sim 4 \times r_{\text{vir}}$).

On the other hand, for $b/kpc \gtrsim 10^3$, the C-model declines more steeply than data, while our best-fitting model properly reproduces the observed flat trend.

The grey circles linked by the dash–dotted line show the EW$_{H_\text{I}}(b)$ profile obtained from $z = 4$ synthetic spectra, once rescaled to the $r_{\text{vir}}$ of the model which reproduces $z = 0.01$ observations. The good agreement between the synthetic and observed EW$_{H_\text{I}}(b)$ profiles shows that our modelling of the CGM reproduces observations, and favours the scenario suggested by Chen (2012) of a redshift-independent CGM profile. As a further support to this idea, we also show (green squares) CGM observations at $z \simeq 2.2$ by Steidel et al. (2010), which are perfectly consistent both with $z = 0.01$

5 Supported by the lack of evolution of CGM profiles from $z = 2$ to 0 (Chen 2012), we assume $\rho_{\text{pp}}$ to be redshift independent in equation (1).

Figure 4. Probability distribution function (PDF) of mean metallicity ($\langle Z \rangle$) and column density ($N_{H_\text{I}}$) for an $M_h = 10^{11} M_\odot$ galactic environment. The colour bar quantifies the PDF weighted by the l.o.s. number. The black solid lines indicate 68, 95 and 99 per cent confidence levels.

4 PROJECTED $\Delta Z$ RELATION

Inspired by the $\Delta Z$ relation found in the ISM/CGM, we investigate whether the mean metallicity along a simulated l.o.s. ($Z$) correlates with the $N_{H_\text{I}}$ distribution of our galactic environments. We compute $\langle Z \rangle$ through the following equation: $\langle Z \rangle = \int_{N_{H_\text{I}}} Z dN_{H_\text{I}}$.

In Fig. 4, we plot the probability distribution function (PDF) of $N_{H_\text{I}}$, and $\langle Z \rangle$ for a simulated environment characterized by $M_h \simeq 10^{11} M_\odot$. Consistently with observations of the CGM in the

\[ \langle Z \rangle = \frac{\int_{N_{H_\text{I}}} Z dN_{H_\text{I}}}{\int_{N_{H_\text{I}}} dN_{H_\text{I}}} \]
proximity of $M_\text{h} \simeq 10^{11} \, M_\odot$ haloes (i.e. Jia Liang & Chen 2014), we find an upper limit of $(Z) < 10^{-1} \, Z_\odot$ in the simulated CGM.

Fig. 4 shows that $(Z)$ tightly correlates with $N_{\text{HI}}$ only in the ISM, which displays both high column density ($N_{\text{HI}} \gtrsim 10^{19} \, \text{cm}^{-2}$) and high mean metallicity $(Z \gtrsim 10^{-1.5} \, Z_\odot)$ values. However, for the CGM/IGM, the underlying tight $\Delta - x Z$ correlation is somewhat blurred, once projected into the $N_{\text{HI}}$ and $(Z)$ variables, which present larger dispersions. This result implies that H i absorption studies do not allow us to precisely constrain the CGM metallicity, as a consequence of a strong $N_{\text{HI}} - (Z)$ degeneracy.

Such a degeneracy can only be broken by adding metal absorption line information. In this case, proximity effect of ionizing sources may turn out to be crucial in determining the different ionization levels of metal atoms. We defer to a future work a proper inclusion of these radiative transfer effects in our simulation. This will allow us to correctly interpret high-$z$ CGM/IGM metal absorption line observations (e.g. D’Odorico et al. 2013; Gonzalo Díaz et al. 2014).

5 CONCLUSIONS

We have used a cosmological metal enrichment simulation (P14) to study the CGM/IGM properties of high-$z$ galaxies, by analysing the H i absorption profiles of the simulated galactic environments. The main results can be summarized as follows.

1. At $z = 4$, the gas radial density profiles in galactic environments are self-similar once scaled with the virial radius of the system, and can be fitted by a piecewise power law ($\rho_{\text{sp}}$, equation 1).

2. Using simulations, we have produced mock H i absorption spectra which are then analysed using the largest gap statistics to identify CGM absorption features. As a consistency check of the EW$_{\text{HI}}$ model, we have verified that it can reproduce the analogous profile deduced from the synthetic spectra.

3. Our analytical model (calibrated at $z = 4$) successfully reproduces CGM/IGM observations both at $z \simeq 0$ (Jia Liang & Chen 2014) and at $z \simeq 2.2$ (Steidel et al. 2010), possibly suggesting that the density profiles evolve very weakly with redshift.

4. We have investigated the relation between the mean metallicity along a simulated l.o.s. $(Z)$ and the $N_{\text{HI}}$ distribution of galactic environments. Consistently with metal absorption line observations of Jia Liang & Chen (2014), we find $(Z) < 10^{-1} \, Z_\odot$ in the CGM; however, the strong $N_{\text{HI}} - (Z)$ degeneracy does not allow us to constrain the CGM metallicity through H i absorption studies alone, and metal absorption line information is required for this goal.

ACKNOWLEDGEMENTS

We are grateful to E. Komatsu and L. Vallini for fruitful discussions.

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