The Lyα forest around high-redshift galaxies
M. Bruscoli, A. Ferrara, S. Marri, R. Schneider, A. Maselli, E. Rollinde, B. Aracil

To cite this version:

HAL Id: hal-04111205
https://hal.science/hal-04111205
Submitted on 9 Jun 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
The Lyα forest around high-redshift galaxies

M. Bruscoli, A. Ferrara, S. Marri, R. Schneider, A. Maselli, E. Rollinde and B. Aracil

1 Dipartimento di Astronomia, Università degli Studi di Firenze, Largo E. Fermi 2, 50125 Firenze, Italy
2 SISSA/International School for Advanced Studies, Via Beirut 2-4, 34014 Trieste, Italy
3 Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
4 Institut d’Astrophysique de Paris, 98bis Boulevard d’Arago, 75014 Paris, France

Accepted 2003 May 9. Received 2003 April 29; in original form 2002 December 4

ABSTRACT
Motivated by the relative lack of neutral hydrogen around Lyman-break galaxies deduced from recent observations, we investigate the properties of the Lyα forest around high-redshift galaxies. The study is based on improved numerical SPH simulations implementing, in addition to standard processes, a new scheme for multiphase and outflow physics description. Although on large scales our simulations reproduce a number of statistical properties of the intergalactic medium (because of the small filling factor of shock-heated gas), they underpredict the Lyα optical depth decrease inside 1 Mpc of the galaxies by a factor of ≈15. We interpret this result as arising from the combined effect of infall occurring along the filaments, which prevents efficient halo gas clearing by the outflow, and the insufficient increase of (collisional) hydrogen ionization produced by the temperature increase inside the hot, outflow-carved bubble. Unless either feedback is not properly modelled in cosmological simulations or an observational selection bias is present, we speculate that local photoionization could be a viable explanation to solve the puzzle.

Key words: intergalactic medium – quasars: general – cosmology: theory.

1 INTRODUCTION
Galaxies form from the intergalactic medium (IGM), process such gas into stars, and possibly re-eject a fraction of it, enriched by nucleosynthetic products, back into the intergalactic space via powerful supernova-driven outflows (Mac Low & Ferrara 1999; Ferrara, Pettini & Shchekinov 2000; Madau, Ferrara & Rees 2001; Scannapieco, Ferrara & Madau 2002; Theuns et al. 2002). The energy deposition connected to these processes is expected to leave at least some detectable imprints on the physical state of the IGM. Thus, it is conceivable that such signatures can be studied through QSO absorption-line experiments. Naively, the presence of hot outflowing gas should result primarily in two effects: (i) a decrease of the gas density and (ii) an increase of the temperature caused by shock heating (acting in conjunction with photo-heating by the UV background) in a large (several hundred kpc) region around the perturbing galaxy. Both these occurrences would imply an increasingly more transparent Lyα forest when approaching the galaxy, i.e. a galactic proximity effect. Quantitative confirmation of this scenario has faced tremendous difficulties, standing the complications of the physics of star formation, explosions and metal mixing in multiphase media. Hence, most simulations to date had to rely on ad hoc recipes for such processes.

Nevertheless, these ideas have stimulated the first challenging observations aimed at detecting the imprints of galaxy–IGM interplay. Adelberger et al. (2003, hereafter A03) obtained high-resolution spectra of 8 bright QSOs at 3.1 < z < 4.1 and spectroscopic redshifts for 431 Lyman-break galaxies (LBGs) at lower redshifts. By comparing the positions of the LBGs with the Lyα absorption lines in QSO spectra, indeed they conclude that within ≈0.5 h−1 (comoving) Mpc of the galaxies little H i is present; on the contrary, between 1 and 5 h−1 Mpc an H i excess with respect to the IGM mean is detected. This simple interpretation might be at odds with the results of a VLT/UVES study of the Lyα forest in the vicinity of the LBG MS1512-cB58 showing the opposite trend (Savaglio, Panagia & Padovani 2002), i.e. an absorption excess close to the galaxy.

Numerical simulations have also noticeable difficulties reproducing A03 results as discussed by Croft et al. (2002) and Kollmeier et al. (2002); however, these studies lack a self-consistent treatment of multiphase gas structure and/or outflow dynamics. Here we revisit A03 results through SPH simulations (Marri et al., in preparation) that implement a new scheme for multiphase hydrodynamics and, more importantly, a physically meaningful outflow treatment; the full description of the code and of the tests made are given in Marri.
& White (2002). We then derive synthetic absorption-line spectra along lines of sight randomly traced through the simulation box at \( z \approx 3 \) and compare them directly with A03 data to investigate galactic feedback effects on the IGM.

## 2 Simulations and Data Analysis

We have performed hydrodynamic simulations for a \( \Lambda \) CDM cosmological model with \( \Omega_m = 0.3, \Omega_b = 0.7, \Omega_{\Lambda} = 0.04 \) and \( h = 0.7 \text{ km s}^{-1} \text{ Mpc}^{-1} \). The initial power spectrum is cluster-normalized (\( \sigma_8 = 0.9 \)). The choice of these parameters is based mainly on measurements of cosmic microwave background (CMB) anisotropies (e.g. Balbi et al. 2000; Netterfield et al. 2002; Pryke et al. 2002) and the abundance of galaxy clusters (e.g. Viana & Liddle 1996); periodic boundary conditions are adopted. We first obtained a set of low-resolution runs (64\(^3\) particles for both gas and dark matter) in a 7 \( h^{-1}\text{Mpc} \) comoving cube; these runs serve as a guide for more computationally expensive runs and for testing purposes. We consider a first model where the IGM multiphase structure and galaxy outflows are deliberately ignored and a second one which includes a description of both these physical effects. We will refer to these runs as SPH and MFB, respectively, with exactly the same meaning adopted in the description of the low-resolution CDM test problem described in Marri & White (2002). The high-resolution run, on which the main results of the present analysis are based, is a 128\(^3\) particles simulation in a 10.5 \( h^{-1}\text{Mpc} \) comoving Mpc box. For this run we only studied the full MFB model.

In all the above cases, the physical processes, the numerical schemes (with the values of the corresponding numerical parameters) adopted, and a number of different test cases aimed at assessing the robustness and effectiveness of the feedback scheme are fully reported in Marri & White (2002). In addition, in all the numerical experiments used for this work, we include the effects of a UV background produced by QSOs and the abundance of galaxy clusters (e.g. Viana & Steinmetz 1997a). For additional discussion on this formula, see e.g. Rauch, Haehnelt & Steinmetz (1997a).

To compare observations and simulations at best it is necessary to degrade the synthetic spectra to account for the uncertainties affecting the observed spectra. We perform such procedure through the following steps: (i) continuum normalization at the highest flux value in each spectrum; (ii) convolution with the instrumental profile; (iii) sampling owing to spectrograph spatial resolution; (iv) addition of instrumental noise (see Rauch et al. 1997b; Theuns et al. 1998; McDonald et al. 2000; Petry et al. 2002). As most of the data we compare with are taken with the Keck/HIRES spectrograph we adopt the following instrumental characteristics: FWHM = 8.0 km\(s^{-1}\), pixel spectral resolution \( \Delta \lambda = 0.05 \AA \) and signal-to-noise ratio \( S/N = 50 \) at the continuum (Gaussian noise is assumed). The low-resolution box has a wavelength extent of \( \Delta \lambda_{\text{box}} = 13.46 \AA \) (\( \Delta \lambda_{\text{box}} = 20.83 \AA \)); hence, degraded spectra in the two cases are made of 269 and 417 pixels, respectively.

## 3 Results

As a general sanity check of the simulations we have first confronted the simulated statistical properties of the Ly\(\alpha\) forest with the observed ones. The most obvious comparison involves the probability distribution function (PDF) of the transmitted flux. In Fig. 1 we plot the PDF as a function of the flux \( F \) for the low-resolution (both MFB and SPH runs) and high-resolution simulations (MFB case only) and compare them with the observational data of McDonald et al. (2000). No scaling of the simulated flux to the observed mean flux has been applied. The general agreement is quite good through all the flux range and for all three cases. The discrepancy between simulations and data at high fluxes is probably due to the uncertainties in the data continuum fitting (McDonald et al. 2000; Croft et al. 2002). Surprisingly, it appears that the inclusion of multiphase and outflow physics, not considered in the pure SPH run, does not affect the distribution in a sensitive manner. In other words, galactic outflows leave the Ly\(\alpha\) forest unperturbed. This result is in agreement with that recently found by Theuns et al. (2002), who interpreted it as an indication that galactic outflows tend to propagate preferentially in the voids leaving the Ly\(\alpha\) absorbing filaments virtually unaffected. As an additional check we have calculated the Doppler parameter, \( b \), and the \( \Delta \) column density distribution, and compared them with two QSOs observations at \( z_{\text{obs}} = 3.38 \) and \( z_{\text{obs}} = 3.17 \) by Hu et al. (1995). The values of \( b \) and \( N_{\text{HI}} \), for each absorber in the synthetic spectra have been derived using the fitting program AUTOVP. The experimental \( b \) distribution is well reproduced both by the SPH and MFB (low-resolution + high-resolution) runs at similar quality level (simulated and observed distributions
The Ly\(\alpha\) forest around high-\(z\) galaxies

Figure 1. Probability distribution function of transmitted flux at \(z = 3.17\) for the low-resolution simulations MFB (solid line) and SPH (dotted) runs, and at \(z = 3.27\) for the high-resolution MFB run (dot-dashed). The points represent the observational data (McDonald et al. 2000) at \(z = 3\).

peak both around \(b \sim 20\ \text{km s}^{-1}\). However, simulated spectra tend to slightly overproduce lines with \(10 < b < 22\ \text{km s}^{-1}\) and underpredict lines with \(25 < b < 50\ \text{km s}^{-1}\). A similar effect has already been noted by Theuns et al. (1998). These authors propose a number of possible explanations for this behaviour: physical (He\(\Pi\) reionization, radiative transfer effects), numerical (resolution) and related to data analysis (fitting procedure). Our results seem to indicate that numerical artefacts should not be the dominant factor. As for the \(\text{H}\ I\) column density distribution, the MFB case seems to reproduce the observational data for \(\log N_{\text{HI}} > 15.5\) somewhat better; for smaller values of \(N_{\text{HI}}\) the differences between the two runs are negligible.

In Fig. 2 we show a temperature map from a slice through the high-resolution box at \(z = 3.27\). Hot bubbles (\(T \approx 10^6\ \text{K}\)) of shocked gas produced by outflows around the parent galaxies are clearly apparent. Their sizes range from \(\approx 0.5\ \text{Mpc} h^{-1}\) to \(\approx 2\ \text{Mpc} h^{-1}\), and their shape appears in some case rather jagged as a result of the interaction with the inhomogeneous ambient medium. The volume filling factor of gas with temperature above \(10^5\ \text{K}\) is 14 per cent. The internal structure of the bubbles can be inspected more quantitatively in Fig. 3, where the comparison between SPH and MFB is shown (low-resolution case) for various physical quantities (hydrogen density, \(n_{\text{H}}\), ionization fraction, \(x_{\text{HI}}\), gas temperature, \(T\), and peculiar velocity, \(v_{\text{pec}}\)) along the LOS through the centre of the most massive galaxy \(M_{\text{tot}} = 1.5 \times 10^{11}\ \text{M}_\odot h^{-1}\) in these simulations; the galaxy position corresponds to the density peak at \(x \approx 6.8\ \text{Mpc} h^{-1}\).

In both simulations the star formation rate in this galaxy is \(5.6\ \text{M}_\odot \text{yr}^{-1}\) for the MFB (SPH) models. Owing to its suitable mass, size and star formation rate this galaxy might reasonably be taken as a LBG template. A striking result of the comparison between the two models shows that, although outflows are able to heat the halo/IGM gas up to high temperatures out to more than \(1\ \text{Mpc} h^{-1}\) from the galaxy, they do not seem able to modify its density structure in a sensitive way. Hence the density in the surroundings remains high and close to that set up by the process of galaxy formation. Close to the galactic centre the outflow peak speed is about \(130\ \text{km s}^{-1}\), but this value rapidly decreases as kinetic energy is used to counteract the pressure of intergalactic accreting gas, raining onto the galaxy at essentially the escape speed of the system, roughly \(150\ \text{km s}^{-1}\). The stalling radius is seen at the zero-crossing of \(v_{\text{pec}}\), approximately \(0.3\ \text{Mpc} h^{-1}\) away from the outflow source. The relative insensitivity of the density to the SN energy injection can be interpreted as the fact that the outflow velocities are lower than the escape speeds and hence the flow is confined by inflow.
displacement to the redshift of each galaxy with r.m.s. $\sigma_{\text{r}} = 0.002$, which represents the $1\sigma$ error of the measure. This procedure improves the result, as now galaxy centres do not coincide perfectly with density peaks, but to an extent insufficient to explain the data.

4 CONCLUSIONS

Motivated by the recent observational results of A03, we have studied, with the help of a set of cosmological simulations including star formation in multiphase gas and outflows from galaxies, the effects of galaxy formation/activity on the properties of the surrounding Ly$\alpha$ forest. Although on large scales our simulations can reproduce remarkably well a number of statistical properties of the IGM, they fail to predict the observed Ly$\alpha$ flux increase in regions close to the galaxies themselves. The success can be ascribed to two concomitant effects: (i) outflows preferentially expand in regions of low density (voids) thus preserving the filaments responsible for the Ly$\alpha$ absorbing network; (ii) the hot bubbles fill a relatively small fraction of the cosmic volume ($\approx 14\%$ per cent in our simulations). Support to the first hypothesis emerges also from an inspection of the velocity field in the surrounding of the most massive galaxy in the simulation: the inflow of gas from low-density regions is blocked by the bubble expansion, but it proceeds basically unimpeded along the filaments (see Marri et al., in preparation).

Much more puzzling is instead the reason for the opacity excess (with respect to real data) we see in the simulation in the inner Mpc field as a leftover of its formation. Also, a large fraction of the outflow energy is used to counteract the infalling gas ram pressure which tends to pile up the gas into the galaxy. The temperature increase close to galaxies amplifies the magnitude of the collisional ionization rate, which becomes larger than the equivalent photoionization rate for $T \gtrsim 10^5$ K. In this case the HI neutral fraction $x_{\text{HI}}$ is independent of gas density and remains at roughly the same level as in the general IGM. Therefore, collisional ionization is not sufficient to balance the opacity increase induced by the density raise and the transmitted flux drops accordingly to the latter.

What are the possible alternative explanations for the observed flux trend? In spite of the many efforts to properly model such process, feedback prescriptions still remain rather uncertain and the discrepancy with the data might well arise from such limitation. However, although different schemes and implementations have been used here and in the similar works of Croft et al. (2002) and Kollmeier et al. (2002), they produce little effect on the final outcome, unless extreme (and probably unphysical) recipes are used as a last resort. The presence of a bias in the data produced by a preferential selection effect of low Ly$\alpha$ absorption LBGs has already been suggested by Croft et al. (2002). Another possibility is provided by photoionization, particularly if one recalls the recent results by Steidel, Pettini & Adelberger (2001), who detected flux beyond the Lyman limit (with significant residual flux at $\lambda < 912$ Å) in a composite spectrum of 29 LBGs at $z = 3.4$, a clue of a conspicuous escape probability of ionizing radiation from these objects. As mentioned above, the A03 data would require an optical depth (or equivalently a $x_{\text{HI}}$, assuming a prescribed density profile) a factor $\approx 15$ smaller. If this can be achieved with the ionizing flux coming from galaxies must be proved with detailed radiative transfer calculations which are currently ongoing (Maselli et al., in preparation). The first attempt using simplified analytical and/or post-processing techniques to account for local photoionization (Croft et al. 2002; Kollmeier et al. 2002) have lead the above authors to preliminarily
conclude that this process cannot account for the deduced transparency of the Lyα forest. However, a fully self-consistent, physically accurate description of the problem is awaited in order to draw a final conclusion.

ACKNOWLEDGMENTS

This work was partially supported by the Research and Training Network ‘The Physics of the Intergalactic Medium’ set up by the European Community under the contract HPRN-CT2000-00126 RG29185. MB thanks P. Petitjean for discussions and hospitality at IAP. We are grateful to S. Bianchi for help with AUTOVP and discussions.

REFERENCES


This paper has been typeset from a TeX/LaTeX file prepared by the author.