UV background fluctuations traced by metal ions at \( z \approx 3 \)

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ABSTRACT

Here we investigate how LyC-opaque systems present in the intergalactic medium at \( z \approx 3 \) can distort the spectral shape of a uniform UV background (UVB) through radiative transfer (RT) effects. With this aim in mind, we perform a multi-frequency RT simulation through a cosmic volume of \( 10^{4} \, \text{cm}^{-3} \) scale polluted by metals, and self-consistently derive the ions of all the species. The UVB spatial fluctuations are traced by the ratio of He II and H I column density, \( \eta \), and the ratio of C IV and Si IV optical depths, \( \zeta \). We find that: (i) \( \eta \) spatially fluctuates through over-dense systems \( (\Delta) \) with statistically significant deviations \( \delta \eta > 25\% \) in 18\% of the volume; (ii) same fluctuations in \( \zeta \) are also present in 34\% of the enriched domain (only 8\% of the total volume) and derive from a combination of RT induced effects and in-homogeneous metal enrichment, both effective in systems with \( \Delta > 1.5 \).

Key words: Cosmology: theory - Cosmic UV background - IGM - metal ions

1 INTRODUCTION

Since the first observations, the He II opacity of the intergalactic medium (IGM) at \( z \approx 3 \) has been interpreted as "patchy" and highly in-homogeneous (Reimers et al. 1997; Hogan et al. 1997; Heap et al. 2000; Smette et al. 2002; Syphers et al. 2011; Syphers & Shull 2014), as highlighted by the Ly-\( \alpha \) forest parameter \( \eta \). In a photo-ionised IGM, \( \eta \) is proportional to the UV background spectral shape (UVBSS) and its scatter in space could reflect spatial fluctuations of the UVB at the ionisation edges of H I and He II (Miralda-Escude 1993). In the last twenty years different interpretations were provided on the origin of these fluctuations. Spectroscopic observations reported variations of \( \eta \in [20 \, 200] \) over scales of \([2 \, 10] \, \text{Mpc} \) (Shull et al. 1999; Fardal et al. 1998; Fechner & Reimers 2007), which could be interpreted as a local ionisation effect in the proximity of quasars (Shull et al. 2004, 2010; Worseck et al. 2007). A decrease of \( \eta \) in redshift, on the other hand, could indicate an evolution in the UVBSS (Zheng et al. 2004). Optical depth ratios from metal lines have been often suggested as additional/independent probes of UVBSS spatial variations: \( \zeta \equiv \tau_{\text{Si IV}}/\tau_{\text{C IV}} \) for example, is sensitive to the UVBSS on either side of the He II ionisation edge (Songaila et al. 1995; Songaila & Cowie 1996; Giroux & Shull 1997; Savaglio et al. 1997; Songaila 1998) and to \([\zeta / \text{C}]/[\text{Si} / \text{C}]\)^{2}. This optical depth ratio was observed to abruptly change around \( z = 3 \) by Songaila (1998) and interpreted as a sudden hardening of the UVB; a redshift evolution of \( \zeta \) was also found by Agafonova et al. (2005, 2007) and Levshakov et al. (2008). Independent measurements, on the other hand, did not confirm the previous findings (Kim et al. 2002; Aguirre et al. 2004). Thus far observations are too scarce to draw a definitive conclusion on the amplitude of the UVBSS fluctuations and on their significance level (e.g. see McQuinn & Worseck 2014 for a case against fluctuations).

Most models of the UVB are not suitable to address this problem because they are generally limited by the assumption of spatial homogeneity and do not account for RT effects, important when density contrasts are present (Maselli & Ferrara 2005, hereafter MF05; Bolton et al. 2006; McQuinn 2009; Ciardi et al. 2012; Meiksin & Tittley 2012; Davies & Furlanetto 2014; Davies et al. 2017). Bolton and Viel (2011, hereafter BV11) adopted a set of spatially

\(^{2}\) \([\zeta / \text{C}]/[\text{Si} / \text{C}]\) \( \equiv \log \left( \frac{\tau_{\text{Si IV}}}{\tau_{\text{C IV}}} \right) - \log \left( \frac{\tau_{\text{Si IV}}}{\tau_{\text{C IV}}} \right) \) \( \approx 0.142 \). This value depends on the relative abundance \( n \) of C and Si polluting the gas and the solar composition model. Here we follow Grevesse & Sauval (1998) to be consistent with the adopted version of Cloudy.

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homogeneous UVB models confirming fluctuations in $\eta$ but they did not find any significant difference in the values of $\zeta$ across models.

By performing a RT simulation of a spatially uniform UVB\(^3\) through a realistic cosmic web polluted by metals, here we show that both random gas clumps of the IGM and RT effects can induce spatial fluctuations in the UVB. These distortions are traced as scatter in space of $\eta$ and $\zeta$ and computed by the new features of the cosmological RT code CRASH3 (Graziani et al. 2013, hereafter GR13). We find that: (i) non negligible spatial oscillations of $\eta$ and $\zeta$ come naturally from both RT effects and in-homogeneous distribution in space of gas over-densities $\Delta^4$; (ii) $\zeta$ can be used as tracer of UVBSS in the metal enriched sub-domain but one has to be aware of the fact that it suffers the complex interplay between radiative and chemical feedback.

This paper is structured as follows. In Section 2 we introduce the numerical simulations, while Section 3 discusses the fluctuations in $\eta$ and $\zeta$. Section 4 finally summarizes the conclusions.

## 2 NUMERICAL SIMULATIONS

The galaxy formation simulation adopted in this work was performed on a box of $10^6 \text{Mpc}^{-1}$ through a realistic cosmic web polluted by metals, as described in Maio et al. (2010). The code includes the whole set of chemistry reactions leading to molecule creation and destruction, as well as metal production and spreading. Metals are released by AGB stellar winds and supernovae (SNII, SNIIa) explosions following star formation and according to the stellar lifetimes and production yields. They are successively spread over the neighbours of stellar particles according to the SPH kernel (Tornatore et al. 2007) within a kinetic feedback scheme accounting for winds with velocity of $500 \text{km s}^{-1}$. A cosmic UVB (Haardt & Madau 1996, hereafter HM96) is also included as photo-ionisation radiation field.

One density snapshot at redshift $z \approx 3$ was ionized after mapping gas and metals on a Cartesian grid of resolution $N_x^3 = 128^3$ cells. Its cosmic web is enriched in $\approx 23\%$ of the total domain: $\approx 17\%$ has metallicity $Z < 0.1Z_\\odot$, while only $\approx 1\%$ has $Z > 1Z_\\odot$. The contribution of metals to the gas cooling function adopted in the RT simulation is also accounted for, as described in GR13.

For consistency with the hydrodynamic simulation, CRASH3 adopts a HM96 UVB sampled by emitting $10^4$ photon packets from $32^3$ grid nodes uniformly covering the cosmic volume\(^6\). The HM96 spectral shape, defined as

$$\frac{J(\nu)}{J_{912}}$$

is sampled by 101 bins, more concentrated around the ionisation frequencies of H and He and extends up to $r_{\text{max}} \approx 124 \text{ Å} (E_{\text{c,max}} \approx 100 \text{ eV})$ to allow a direct comparison with the MF05 results\(^8\). During the run it is tracked in regions with $Z > 0$ to derive metal ions\(^9\) with the CLOUDY (v.10, Ferland et al. 1998) module embedded in CRASH3. Periodic boundary conditions are set up by repeating the escaping packets 10 times to approximately cover the mean free path of ionizing photons at $z = 3$ (approx. $100h^{-1} \text{ Mpc}$, Fan et al. 2002). The simulation starts from a neutral gas at $T_0 = 100 \text{ K}$ and proceeds until an ionisation equilibrium is reached ($t_{eq} = 5.5 \cdot 10^6 \text{ yr}$)\(^10\). The resulting volume averaged ionisation fractions are $\xi_{\text{HII}} \approx 0.999997$, $\xi_{\text{HeII}} \approx 0.036899$ and $\xi_{\text{HeI}} \approx 0.963097$\(^11\).

\(^{3}\) The generated UVB shape and intensity, as well as its uniform emission in space, are pre-assumed from a selected model with no explicit assumptions on source properties.

\(^{4}\) $\Delta \equiv \rho / \rho_0$, where $\rho$ is the gas density in a point of space (hereafter a cell of a grid) and $\rho_0$ the volume density value.

\(^{5}\) Hereafter the gas metallicity (or equivalently the metal mass fraction) is defined as $Z \equiv M_Z / M_{\text{gas}}$, where $M_Z$ is the mass of the total mass of the elements with atomic number higher than 2, and $M_{\text{gas}}$ is the total mass of the gas. $Z_\\odot = 0.0126$ as in Asplund et al. (2004).

\(^{6}\) More details on the UVB numerical scheme can be found in MF05 and will be provided in Graziani et al., in prep. Here note that in our simulation the adoption of a uniform emission grid minimizes by design the intrinsic Monte Carlo noise and guarantees the UVB uniformity assumption with high precision (see Section 3.1).

\(^{7}\) As usual, $J(\nu)$ is the spectrum at frequency $\nu$ and $J_{912}$ is its value at 912 Å.

\(^{8}\) As CRASH3 treats the gas ionization by UV photons and does not account for the physics of X-rays and secondary ionization (but see Graziani et al. 2018 for a novel implementation), only the UV range in the original HM96 UV/X-ray spectrum has been selected.

\(^{9}\) Note that the radiation tracking is not necessary to compute H and He ionisation (see GR13 for more details).

\(^{10}\) Initial conditions consistent with the reionization history could be obtained from reionisation simulations of both H and He. We defer this investigation to a future work having a consistent calculation from reionization simulations accounting for metals.

\(^{11}\) Note that the total number of photons crossing the domain is higher than $10^9$ and guarantees Monte Carlo convergence up to the $10^{-6}$ in the hydrogen ionisation fraction, at equilibrium.
3 RESULTS

Here we show the spatial fluctuations of \( \eta \) and \( \zeta \) at \( t_{eq} \) and we study them as function of \( \Delta \). The relative fluctuation of \( \eta \) (or \( \zeta \)) around the highest probability value (\( \eta_\text{p} \)) of its distribution\(^{12} \) is defined as \( \delta \eta \equiv \left| \frac{\eta - \eta_\text{p}}{\eta_\text{p}} \right| \), while \( \eta \) indicates the volume averaged value. The statistical distributions of both quantities are computed in all the cells in which they are investigated, i.e. the cosmic volume for \( \eta \) and the overdense, metal polluted domain for \( \zeta \).

3.1 Fluctuations of \( \eta \)

To compute \( \eta \) at simulation run-time we adopt the notation of Fardal et al. (1998):

\[
\eta = \frac{\alpha_{\text{HeII}}(T) \ n_{\text{HeII}} \ \Gamma_{\text{HeII}}}{\alpha_{\text{HI}}(T) \ n_{\text{HI}} \ \Gamma_{\text{HI}}} \tag{1}
\]

where \( \alpha_{\text{HeII}} \) and \( \alpha_{\text{HI}} \) are the Case A \( \text{HeII} \) and \( \text{H} \)\text{I} recombination coefficients, while \( \Gamma_{\text{HeII}} \) and \( \Gamma_{\text{HI}} \) are their photo-ionisation rates computed in each cell of the domain.

In Figure 1 we show \( \eta \) in a slice with a central overdense filament enriched by metals. The under-dense regions (\( \approx 33\% \) of the plane, dark-blue areas) are characterized by \( \eta \approx 260 \), while the central filament shows values in the range \( 350 < \eta < 450 \). Higher values, up to \( \eta = 600 \), are found instead in the densest clumps visible at the borders of the figure\(^{13} \). To highlight the tight correlation between \( \eta \) and \( \Delta \), we over-plot \( \Delta \) iso-contour lines. As argued in MF05, at photo-ionisation equilibrium \( \eta \) increases with \( \Delta \) for a combination of reasons: (i) the recombination rates show a weak dependence on \( T \) and then the ratio is expected to weakly reflect the increase of \( T \) in \( \Delta > 1 \) (Theuns et al. 1998); (ii) helium recombines 5.5 times faster than hydrogen and in over-dense regions the ratio \( \frac{\alpha_{\text{HeII}}}{\alpha_{\text{HI}}} \) drives the increase of \( \eta \) with \( \Delta \) as the Universe is more opaque in \( \text{HeII} \); (iii) \( \Gamma_{\text{HeII}} \) is always one order magnitude larger than \( \Gamma_{\text{HI}} \). Note that spatial fluctuations in \( T \) are also present and will be investigated in a companion paper.

Figure 2 shows, as scatter plot, the values of \( \eta \) found in each cell of the cosmic volume as function of their over-density \( \Delta \). The average of \( \eta \) at fixed over-density (\( \eta_f \)) is also shown as reference with red crosses. The yellow transparent area indicates the effects of the CRASH3 numerical noise on \( \eta \), evaluated by propagating a spatially homogeneous UVB through a medium with constant number density\(^{14} \); the fluctuations induced on \( \eta \) by that noise are always lower than 1.5% in all tests. A significant scatter is found around each \( \eta_f \) (red crosses) and around both \( \eta_\text{p} \) (violet solid line) and \( \eta_f \) (dashed green line), computed from the global statistic. Note that regions with \( \Delta < 0.1 \) exhibit a low scatter at fixed number density: 5-8% around \( \eta_f \approx 252 \), with only few cells reaching 15%. In \( 0.1 < \Delta < 10 \), \( \eta_f \) increases with \( \Delta \) and the scatter shows typical statistically significant variations of 20-30%, with values as high as 60% in the range \( 7 < \Delta < 10 \). As discussed in MF05, in very dense regions with \( \Delta > 10 \) recombination dominates over ionisation, inducing an inversion of the trend, with \( \eta_f \) decreasing with increasing \( \Delta \). Finally note that the small cloud of points in which \( \eta < 200 \) (0.1 < \( \Delta < 10 \)) is created by cells hosting photon emission nodes. In these cells in fact our ionization algorithm tends to fully ionize the gas and to lower the value of \( \eta \); their total number is, on the other hand, lower than 1% with a negligible impact on the global statistic. As a comparison, we computed \( \eta_{\text{eq}}(\Delta, Z) \), i.e. the value of \( \eta \) determined by Cloudy photo-ionisation equilibrium models assuming a spatially homogeneous HM96 UVB, as described in Section 2\(^{15} \). All \( \eta_{\text{eq}}(\Delta, Z) \) lie between the values corresponding to the min/max of the gas metallicity (0.01 \( Z_\odot \), dotted; 3 \( Z_\odot \), solid light-blue lines). In under-dense regions \( \eta_{\text{eq}} \approx \eta_f \) because the RT effects are minimized and \( Z \) is usually low.

\(^{12}\) Operationally, the highest probability value is the center of the histogram bin containing the largest number of cells.

\(^{13}\) Note that the periodic boundary conditions applied to the hydrodynamical simulation create quasi-symmetric over-density areas at the volume edges.

\(^{14}\) Here we checked the cases corresponding to \( n_{\text{gas}} \sim 10^{-7}, 10^{-6}, 10^{-5} \) (i.e. \( \Delta \approx 1 \), \( 10^{-4} \) cm\(^{-3} \)). This tests minimize the RT effects and allow to establish the method intrinsic noise once the Monte Carlo convergence is established (see Section 2).

\(^{15}\) While the scatter plot shows points largely deviating from the average values in the entire domain, their significance is established by looking at their statistical distribution in fixed over-density bins.

\(^{16}\) Formula 1 shows that \( \eta_{\text{eq}} \) can vary because of both \( \alpha_{\text{HeII}}(T)/\alpha_{\text{HI}}(T) \) and \( n_{\text{HeII}}/n_{\text{HI}} \), at assigned UVB and \( E_{\nu,\text{max}} \). These terms depend on \( Z \) and \( n_{\text{gas}} \) in each cell; the total computation can then be performed by a grid of models spanning their values. Finally note that the choice of \( E_{\nu,\text{max}} \) implies a less steep \( \eta_{\text{eq}}(\Delta) \) relation with respect to adopting the original HM96 spectral range as the X-ray contribution to helium ionisation is not accounted for (Grzaziani et al. 2018).
Here we discuss the scatter in data (in tension with values found in McQuinn & Worseck (2014). Significantly reduced the fluctuations of $\zeta$ at observed in Heap et al. (2000) and Syphers & Shull (2014) $\zeta$. The statistical distribution of $\eta$ shows $\eta_p \approx 247$ and $\eta \approx 277$. In $\approx 82\%$ of the domain $\delta_T \leq 25\%$, while a fluctuation within $25\% < \delta_T \leq 50\%$ is found in $11\%$ of the cells. Finally, values in $50\% < \delta_T \leq 75\%$ are found in $4\%$ of the domain and a remaining $3\%$ shows $\delta_T > 75\%$.

The above results are in global agreement with MF05, but it should be noted that our statistic shows higher fluctuations when $\Delta > 1$ due to the improved feedback model of the hydrodynamical simulation, which creates sharper density gradients and enhances the RT effects. As a result, the spatial UVB fluctuations increase. Finally, we point out that while our analysis is not meant to quantitatively reproduce observations (this will be addressed in a companion project with an updated UVB model, i.e. Haardt & Madau 2012), the predicted value of $\eta \approx 277$ is consistent with the one observed in Heap et al. (2000) and Syphers & Shull (2014) at $z \approx 3$. Our fluctuation range is reasonable as well, as it is consistent with the estimates in Shull et al. (2004) inferred at a similar scale (i.e. $10 h^{-1}$ Mpc comoving), although it is in tension with values found in McQuinn & Worseck (2014).

Note, though, that the latter results refer to lower redshift data ($z < 2.7$), where the progress of reionization could have significantly reduced the fluctuations of $\eta$.

### 3.2 Fluctuations of $\zeta$

Here we discuss the scatter in $\zeta$, which provides an additional evidence of the UVBSS spatial fluctuations using metal ions. Since CRASH3 does not include the metal contribution to the gas optical depth (see GR13 for more details), $\zeta$ computed in this paper fluctuates as a result of absorption by H and He only, and of in-homogeneous chemical enrichment. Spectral distortions around the ionisation energy of H I and He II impact in fact the ionization of both Si IV and C IV and alter the ratio of their ionization fractions. In addition, fluctuations of $[\text{Si} / \text{C}]$ are expected in different density environments because metals are followed individually during their spreading outside the formation sites. For an easier comparison with BV11, we compute $\zeta$ in each cell of the over-dense, polluted volume as:

$$\zeta = 1.7 \frac{x_{\text{SiIV}}}{x_{\text{CIV}}} 10^{[\text{Si/C}] - 0.77},$$

where $x_{\text{SiIV}}$ and $x_{\text{CIV}}$ are the ionization fractions of Si IV and C IV, respectively. $\zeta$ can then be studied as a combination of two terms: $x \equiv x_{\text{SiIV}} / x_{\text{CIV}}$ (mainly affected by RT) and $y \equiv 10^{[\text{Si/C}] - 0.77}$, reflecting the in-balance of atom abundances created by mechanical and chemical feedback. Hereafter we focus on the sub-domain $\Delta > 1.5$ because it is significantly metal polluted and simultaneously shows large fluctuations in the UVB spectral shape through $\eta$.

Figure 3 shows the scatter plot of $\zeta(\Delta)$. Deviations of $\zeta$ from $\zeta_T$ are present everywhere, but contrary to $\eta$ there is no tight dependence on $\Delta$ and $\zeta_T$ decreases of about $25\%$ from $\Delta < 7$ ($\zeta_T \approx 0.125$) to higher over-densities where $\zeta_T \approx 0.1$.

Large fluctuations (up to several orders of magnitude) are clearly visible around any $\zeta_T$, but when a statistically significant number of cells is considered their amplitude reduces to $\approx 60\%$. In specific cases (see the cloud of violet points) $\zeta$ scatters in $10^{-5} < \zeta < 10^{-3}$ because of the extremely low values of $x (x < 10^{-3})$, i.e. either the spectral shape created in these cells is highly altered by absorption at the ionization potential of Si IV ($\approx 45$ eV) or a hard spectrum generates higher ionization states (see for example the model UVB3 studied in BV11). Another limited set of points (gold cloud) is determined by the conditions: $x = 1$, and $y$ almost constant. In these cells either Si IV and C IV are fully ionized or in ionization states higher than IV. As in Figure 2, the light-blue lines refer to $\zeta_{eq}(\Delta, [\text{Si}/\text{C}])$ computed by assuming a uniform UVB. At constant $[\text{Si}/\text{C}](1.5) \approx 0.62$ (i.e. $y(\Delta) \approx 0.7$, solid line), $\zeta_{eq}(\Delta)$ shows a global decrease of only $4\%$, driven by a decrease of $x$ with increasing $\Delta$. When the UVB is assumed homogeneous in space, the only term inducing significant spatial fluctuations is then $y$. By adopting the min/max values of $y(\Delta)$ we can trace the dashed/dashed-dotted lines, also showing that the maximum variation of $[\text{Si}/\text{C}]$ is found in $1.5 < \Delta < 10$, while it significantly reduces at higher over-density. These extreme cases, on the other hand, must be taken with a grain of salt as they are found in less than $7\%$ of the cells; the scatter of $[\text{Si}/\text{C}]$ from the average value is $\leq 4\%$ in the remaining $93\%$, i.e. $\zeta_{eq}$ is confined in the cyan shadow area.\footnote{Note that (i) the hydrodynamical scheme shows an average $[\text{Si}/\text{C}] \approx 0.77$, perfectly consistent with the one observed in the IGM (Aguirre et al. 2004); (ii) the trend of $\zeta_{eq}(\Delta)$ strictly depends on the specific $E_{acc,max}$ adopted in the computation, as the metal ionization reacts to a spectral range wider than the one of H and He (see GR13 and Graziani et al. 2018 for more details).}

Figure 3. Scatter plot of $\zeta$ (black points) as function of $\Delta$ at $t_{eq}$. The average value at fixed $\Delta$, $\zeta_T$, is shown as red crosses, while the highest probability value $\zeta_{eq}$ as dashed green line. Violet points indicate cells in which $x \equiv x_{\text{SiIV}} / x_{\text{CIV}} < 10^{-3}$, while gold points mark cells in which $x = 1$. Dashed/dashed-dotted light-blue lines show $\zeta_{eq}(\Delta, [\text{Si}/\text{C}])$ computed at the minimum/maximum values of $[\text{Si}/\text{C}](\Delta)$, while a case at the highest probability value of $[\text{Si}/\text{C}](1.5) \approx 0.62$ is shown as a solid line. Finally note that in about $93\%$ of the domain $1.5 < \Delta < 10$, $\zeta_{eq}$ has values in the cyan shadow area.
In this paper we post-process a hydrodynamic simulation which includes metal pollution with the multi-frequency cosmological radiative transfer (RT) code CRASH3 to study the amplitude and statistical relevance of spatial fluctuations of the UV background spectral shape (UVBSS) at the epoch of helium reionisation ($z \approx 3$). As the slope of the UVBSS can not be inferred by direct observations, its fluctuations must be constrained by combining the observed scatter in two quantities sensitive to the shape around the He\textsc{ii} ionisation potential: $\eta \equiv N_{\text{HeII}}/N_{\text{HI}}$ and $\zeta \equiv \tau_{\text{SiIV}}/\tau_{\text{CIV}}$. Note that a theoretical investigation of this problem can not be effectively performed with conventional UVB models which do not include an accurate RT. In this work, for the first time in the literature, we employ a radiative transfer approach through H, He and metal species to evaluate $\eta$ and $\zeta$ self-consistently, guaranteeing that the significant spatial fluctuations obtained are indeed due to the combined effect of metal enrichment and radiation transfer. In particular:

- we find a tight correlation of the $\eta$ parameter and overdense systems of the cosmic web on a scale of $10^{-1}$ cm$^{-1}$ and a resolution of $\approx 78$ h$^{-1}$ kpc; these spatial fluctuations can reach values higher than 25% in 18% of the domain and are due to RT effects through the cosmic web;
- by computing metal ions self-consistently with the RT it is possible to reproduce spatial fluctuations of $\eta$ higher than 25% in 34% of the metal enriched, overdense systems with $\Delta > 1.5$ (i.e. 8% of the total volume). To be effectively used as tracer of the UVBSS, $\zeta$ requires then the presence of a statistically relevant number of polluted, overdense systems along observed lines of sight;
- although radiative effects remain dominant, $\zeta$ depends on both UVBSS distortions and spatial fluctuations of $[\text{Si}/\text{C}]$; we have shown that their combined effects increase the domain in which $\delta \zeta > 25\%$.

Future studies will focus on complementary sources of UVB fluctuations, mainly associated with the variability of quasars at the epoch of helium reionisation, and will compare their statistical significance with the present findings.

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References

Agafonova I. I., Centurion M., Levshakov S. A., Molaro P., 2005, AAP, 441, 9
Agafonova I. I., Levshakov S. A., Reimers D., Fechner C., Tytler D., Simcoe R. A., Songaila A., 2007, AAP, 461, 893
Aguirre A., Schaye J., Kim T.-S., Theuns T., Rauch M., Sargent W. L. W., 2004, ApJ, 602, 38
Asplund M., Grevesse N., Sauval A. J., Allende Prieto C., Kiselman D., 2004, AAP, 417, 751
Bolton J. S., Hachnelt M. G., Viel M., Carswell R. F., 2006, MNRAS, 366, 1378
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Ciardi B., Bolton J. S., Maselli A., Graziani L., 2012, MNRAS, 423, 558
Davies F. B., Furlanetto S. R., 2014, MNRAS, 437, 1141
Davies F. B., Furlanetto S. R., Dixon K. L., 2017, MNRAS, 465, 2886
Fan X., Narayanan V. K., Strauss M. A., White R. L., Becker R. H., Pentericci L., Rix H.-W., 2002, AJ, 123, 1247
Fardal M. A., Giroux M. L., Shull J. M., 1998, AJ, 115, 2206
Fechner C., Reimers D., 2007, AAP, 461, 847
Ferland G. J., Korista K. T., Verner D. A., Ferguson J. W., Kingdon J. B., Verner E. M., 1998, PASP, 110, 761
Giroux M. L., Shull J. M., 1997, AJ, 113, 1505
Graziani L., Maselli A., Ciardi B., 2013, MNRAS, 431, 722
Graziani L., Ciardi B., Glatzle M., 2018, MNRAS, 479, 4320
Grevesse N., Sauval A. J., 1998, SSR, 85, 161
Haardt F., Madau P., 1996, ApJ, 461, 20
Haardt F., Madau P., 2012, ApJ, 746, 125
Heap S. R., Williger G. M., Smette A., Hubeny I., Sahu M. S., Jenkins E. B., Tripp T. M., Winkler J. N., 2000, ApJ, 534, 69
Hogan C. J., Anderson S. F., Rogers M. H., 1997, AJ, 113, 1495
Kim T.-S., Cristiani S., D’Odorico S., 2002, AAP, 383, 747
Levshakov S. A., Agafonova I. I., Reimers D., Hou J. L., Molaro P., 2008, AAP, 483, 19
Maio U., Ciardi B., Dolag K., Tornatore L., Khochfar S., 2010, MNRAS, 407, 1003
Maselli A., Ferrara A., 2005, MNRAS, 364, 1429
McQuinn M., 2009, ApJL, 704, L89
McQuinn M., Worseck G., 2014, MNRAS, 440, 2406
Meiksin A., 2009, Reviews of Modern Physics, 81, 1405
Meiksin A., Tittley E. R., 2012, MNRAS, 423, 7
Miralda-Escude J., 1993, MNRAS, 262, 273
Reimers D., Kohler S., Wisotzki L., Groote D., Rodriguez-Pascual P., Wamsteker W., 1997, AAP, 327, 890
Savaglio S., Cristiani S., D’Odorico S., Fontana A., Giallongo E., Molaro P., 1997, AAP, 318, 347
Shull J. M., Roberts D., Giroux M. L., Penton S. V., Fardal M. A., 1999, AJ, 118, 1450
Shull J. M., Tumlinson J., Giroux M. L., Kriss G. A., Reimers D., 2004, ApJ, 600, 570
Shull J. M., France K., Danforth C. W., Smith B., Tumlinson J., 2010, ApJ, 722, 1312
Smette A., Heap S. R., Williger G. M., Tripp T. M., Jenkins E. B., Songaila A., 2002, ApJ, 564, 542
Songaila A., 1998, AJ, 115, 2184
Songaila A., Cowie L. L., 1996, AJ, 112, 335
Songaila A., Hu E. M., Cowie L. L., 1995, NATURE, 375, 124
Springel V., 2005, MNRAS, 364, 1105
Syphers D., Shull J. M., 2014, ApJ, 784, 42
Syphers D., Anderson S. F., Zheng W., Meiksin A., Haggard D., Schneider D. P., York D. G., 2011, ApJ, 726, 111
Theuns T., Leonard A., Elstathiou G., Pearce F. R., Thomas P. A., 1998, MNRAS, 301, 478
Tornatore L., Borgani S., Dolag K., Matteucci F., 2007, MNRAS, 382, 1050
Worseck G., Fechner C., Wisotzki L., Dall’Aglio A., 2007, AAP, 473, 805
Zheng W., et al., 2004, ApJ, 605, 631