Extended O VI haloes of star-forming galaxies

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ABSTRACT

We consider the evolution of metal-enriched gas exposed to a superposition of the time-dependent radiation field of a nearby starburst galaxy and a nearly invariant (on time-scales of 100 Myr) extragalactic ionization background. Using non-equilibrium (time-dependent) photoionization models, we determine the ionization fraction of the O VI ion commonly observed in the galactic circumference. We then derive the conditions for O VI to appear in absorption in extended galactic haloes, depending on the galactic mass and star formation rate. We have found that the maximum O VI fraction can reach ~0.4–0.9 under the combined action of galactic and extragalactic ionizing radiation fields. We conclude that soft X-ray emission with $E \gtrsim 113$ eV from the stellar population of central star-forming galaxies is the main source of such a high fraction of O VI. This circumstance can explain the high column densities, $N(OVI) \sim 10^{14.5–15.5}$ cm$^{-2}$, observed in the haloes of star-forming galaxies at low redshifts even for relatively low ($\sim 0.01–0.1 Z_\odot$) metallicity. As a result, the requirements for sources of oxygen in extended haloes relax to a reasonably conservative level. We show that, at $z \lesssim 0.5$, the ionization kinetics of oxygen in a relatively dense plasma, $n \gtrsim 10^{-4}$ cm$^{-3}$, of an outer halo exposed to a low extragalactic ionizing flux is dominated by non-equilibrium effects.

Key words: atomic processes – galaxies: haloes – intergalactic medium – quasars: absorption lines – galaxies: starburst – X-rays: galaxies.

1 INTRODUCTION

The strong O VI absorption observed around star-forming galaxies at $z \sim 0.1–0.4$, with impact parameters as high as 150 kpc, reveals huge gaseous galactic haloes (Tumlinson et al. 2011). Even conservative estimates lead to amounts of gas in these that far exceed the gas reservoirs in galaxies themselves. Such a conclusion is based on the assumption that gas in haloes has solar metallicity. The arguments underlying this assumption stem from the standard estimate of oxygen mass from the observed column density (Tumlinson et al. 2011):

$$M_O = 5\pi R^2 \langle N(OVI) \rangle m_{OVI} f_{OVI} \left( \frac{0.2}{f_{OVI}} \right) = 1.2 \times 10^{7} \left( \frac{0.2}{f_{OVI}} \right) M_\odot,$$

(1)

where a typical column density $\langle N(OVI) \rangle = 3 \times 10^{14}$ cm$^{-2}$, the halo radius $R = 150$ kpc, the hit rate correction factor (covering factor) $f_{OVI} = 0.8–1$ is assumed following Tumlinson et al. (2011) and $m_{OVI} = 16 m_H$ is the atomic mass of oxygen. The fractional abundance of O VI under thermal collisional ionization equilibrium never exceeds $f_{OVI} = 0.2$ (e.g. Ferland et al. 1998; Gnat & Sternberg 2007), such that, within this assumption, equation (1) provides a lower estimate of oxygen mass in the halo (Tumlinson et al. 2011). It is readily seen from here that the mass $M_O \sim 10^7 M_\odot$, i.e. around 10–70 per cent of oxygen mass in the interstellar medium (ISM), is indeed a conservative estimate.

In principle, this conclusion that galactic haloes bear such a large gas mass might solve the problem of missing baryons and metals (Bregman et al. 2009; Pettini 1999), though it requires enormously high oxygen production and mass ejection rates. Moreover, the fraction $f_{OVI} = 0.2$ under collisional ionization equilibrium is kept only in a very narrow temperature range: $T = (3–5) \times 10^{5}$ K (e.g. Ferland et al. 1998; Gnat & Sternberg 2007). It is therefore totally unrealistic to assume that all observed haloes keep their temperatures within such a narrow range, independent of distance from the host galaxy.

In their estimates, Tumlinson et al. (2011) used the ionic fractions calculated under collisional and/or photoionization equilibrium conditions, i.e. independent of time (Ferland et al. 1998). However, the ionization state of gas situated in a time-dependent (non-equilibrium) environment can differ qualitatively from one settled in equilibrium, particularly for solar metallicity (Vasiliev 2011). This difference can be smaller for low-density gas exposed...
to a strong ionizing field. However, in the process of galactic evolution, both the magnitude and the shape of the radiation spectrum can change. In addition, the extragalactic spectrum, which can be important on the periphery of galactic haloes, also evolves (Haardt & Madau 2001; Faucher-Giguère et al. 2009). Under such conditions, it is natural to expect the ionic composition to experience time variations.

In this article, we therefore concentrate on the question of whether evolution of the ionizing radiation field can result in considerable changes of the fractional ionization of oxygen, such as to make estimates of the gas mass in galactic haloes more reliable. In the next sections, we will demonstrate that indeed under time-dependent conditions the observed column densities of O VI correspond to haloes at least half an order of magnitude less massive.

The article is organized as follows. In Section 2, we describe the details of the model. In Section 3, we present our results. Section 4 summarizes the results.

2 MODEL DESCRIPTION

The thermal and ionization state in our model are fully time-dependent: the model involves the ionization and thermal evolution of gas located at radii ≈50–300 kpc in the galactic halo, exposed to extragalactic and galactic time-dependent ionizing radiation fields.

2.1 Time-dependent ionization

In this article, we only briefly touch the main features of calculation of the ionization and thermal evolution of gas immersed in external time-dependent ionizing radiation. The details can be found in Vasiliev (2011). We study the ionization and thermal evolution of a Lagrangian gas element: the gas parcel is assumed to be optically thin to external ionizing radiation. In the calculations, we include all ionization states of the elements H, He, C, N, O, Ne, Mg, Si and Fe. We take into account the following major processes: photoionization, multi-electron Auger ionization process, collisional ionization, radiative and dielectronic recombination, collisional excitation as well as charge transfer in collisions with hydrogen and helium atoms and ions.

The total cooling and heating rates are calculated using the photoionization code CLOUDY (ver. 10.00: Ferland et al. 1998) as a subroutine. More specifically, we input into the CLOUDY code a given set of all ion fractions X_i calculated at temperature T, gas density n and external ionization flux J(v) and obtain the corresponding cooling and heating rates. The latter also includes Compton heating from X-rays. For the solar metallicity, we adopt the abundances reported by Asplund, Grevesse & Sauval (2005), except for Ne, for which the enhanced abundance is adopted (Drake & Testa 2005). In all calculations we assume the helium mass fraction Y_H = 0.24, which corresponds to [He/H] = 0.081 and is close to the observed value (Izotov & Thuan 1998).

We solve a set of 96 coupled equations (95 for ionization states and one for temperature) using a variable-coefficient ordinary differential equation solver (Brown, Byrne & Hindmarsh 1989). We consider two regimes of gas evolution: isochoric and isobaric. The isochoric regime suggests that the gas density in a cloud is kept constant, while in the isobaric model the gas pressure is assumed constant. The two regimes correspond to two opposite limits of the ratio between the cooling and sound-crossing times: t_c = kT/πn and t_s = R/c_s, correspondingly. In the external heating radiation field, isobaric models show essentially similar thermal and ionization evolution, though on longer time-scales due to decreasing density coupled to increasing temperature. This results in an increase of the cross-section of gas clouds, such that their covering factor increases as well.

2.2 Galaxy evolution

In the process of galaxy evolution, the stellar content changes: massive stars produce enormous numbers of UV photons and ultimately form compact objects, which emit hard ionizing photons. The spectrum of the ionizing radiation escaping the galactic ISM and exposing the halo further depends on the amount of metals in the ISM disc absorbing ionizing photons and thus on the chemical evolution of the galaxy. In order to follow the evolution of the stellar mass, metallicity and galaxy spectrum, we use the spectrophotometric code PG (Fioc & Rocca-Volmerange 1997). We assume a Schmidt-like power-law star formation rate (SFR): SFR(t) = M_\odot^p / p_t, a typical SFR for massive star-forming galaxies, where M is the normalized mass of gas in M_\odot. In some regions of the galaxy, the SFR can be inhibited by gas outflows from the disc, however, when averaged over the whole disc the SFR remains sufficiently high over the whole period of active star formation. In our models we assumed a closed-box regime. In general, this cannot be applied to galaxies with active star formation. However, many parameters related to mass and energy exchange between galaxies and the intergalactic medium, such as the rates of mass ejection from and mass accretion from the ambient medium, metallicity and the corresponding cooling rate, clustering of SNe explosions, etc., are highly uncertain and hard to describe coherently phenomenologically.

2.3 Time-dependent UV/X-ray backgrounds

Gas in galactic haloes is exposed to a cumulative ionizing background consisting of extragalactic and galactic components. The extragalactic component is uniform on galactic halo scales and is nearly constant on time-scales ~100 Myr, while changing significantly on longer time-scales. For the extragalactic background, we accept the spectrum described by Haardt & Madau (2001). Its evolution covers redshifts z = 0–9 divided into 49 equally spaced log bins. Contributions from possible flux sources vary over cosmological time and irregular changes in different bands of the spectrum with redshift can take place. For this reason, a simple linear approximation between neighbouring redshift bins was used.

The galactic component, in contrast, may change on much shorter time-scales. In general, the corresponding time-scale is close to the lifetime of massive stars, i.e. ~10–20 Myr. This galactic radiation component originates in the central star-forming region and is seen from outer parts of the halo at distances ≥30–50 kpc as a nearly spherical domain of size of ~2–3 kpc.

The ionizing radiation from the stellar population is partly modified by absorption in the interstellar medium of the underlying bulge and disc. In order to account for this absorption, we assume that ionizing photons pass through a layer of neutral gas in the galactic disc with optical depth τ_i = σ_i H N_i + σ_i H e N_i e; throughout the article, N_H = 10^{20} cm^{-2}, N_H e = 10^{19} cm^{-2} are considered as fiducial. The corresponding optical depths at the H I and He I Lyman limits are as high as ~630 and 70, respectively. As a result, only photons with E ≥ 60 eV escape the galaxy and penetrate into halo; the ionizing flux with photons of E > 60 eV decreases as r^{-2}. In what follows, we will discuss the dependence of our results on the H I column density.
In our model, the galactic UV spectrum is calculated by making use of the PEGASE code (Fioc & Rocca-Volmerange 1997), which gives spectral luminosity in the range from 91 Å to 160 µm. In order to extend the spectrum to higher energies (up to \( \sim 10^4 \) eV, responsible for the ionization of highly charged ionic species), we use the empirical relation between the X-ray luminosity and the star formation rate \( 'L_X-SFR' \) (Gilfanov, Grimm-J. & Sunyaev 2004). This relation is well-established for the massive star-forming galaxies considered here.

Overall, the cumulative spectrum varies on time-scales from several to hundreds of millions of years.

2.4 Initial set-up

We consider the gas in the outer haloes of massive (Milky Way type) star-forming galaxies with stellar masses of several \( \times 10^{10} \, M_\odot \). Recent simulations of the Milky Way halo show that it extends up to the virial radius of the Milky Way (i.e. \( \sim 50–300 \) kpc), with densities ranging within \( (0.5–2) \times 10^{-4} \, cm^{-3} \) (Feldmann, Hooper & Gnedin 2013). Observational estimates of the circumgalactic gas density around the Milky Way and other Local Group galaxies give similar numbers: \( (1–3) \times 10^{-4} \, cm^{-3} \) at \( r \sim 40–150 \) kpc (Weiner & Williams 1996; Greveich & Putman 2009; Quilis & Moore 2001; Stanimirović et al. 2002; Anderson & Bregman 2010).

In our calculations, we follow these numbers and set \( n = (0.5–2) \times 10^{-4} \, cm^{-3} \) in the circumgalactic volume. We consider both isochoric and isobaric regimes.

We start the calculations at \( z = 2 \) (the look-back time is around 10 Gyr). This time-scale is nearly the cooling time for hot gas with \( T \sim 10^6 \) K and \( \sim (0.5–2) \times 10^{-4} \, cm^{-3} \) (Feldmann et al. 2013). The last major merging for Milky Way type galaxies is thought to occur earlier than \( z = 2 \) (e.g. Hammer et al. 2007).

The initial ionization and the temperature are set equal to those corresponding to photoequilibrium in gas exposed to the extragalactic Haardt & Madau spectrum at \( z = 2 \). Such a radiation field is sufficient to force low-density gas with \( n \) in the accepted range to settle quickly into photoequilibrium (Vasiliev 2011). Calculations cover physical time-scales much longer than the relaxation time-scale of ionization and thermal processes in gas exposed to the time-dependent spectrum adopted here.

Gas metallicity in our models is assumed to range within \( 10^{-2} \) to \( 0.1 \, Z_\odot \). Higher metallicities are rare in Damped Lyman-alpha (DLA) quasi-stellar objects (QSOs) and DLA Gamma Ray Bursts (GRB) absorbers (Savaglio 2009). The lower limit lies around ten times higher than the upper limit of the intergalactic medium metallicity at \( z \sim 2–3 \) (e.g. Cowie et al. 1995; D’Odorico et al. 2010).

3 RESULTS

3.1 SFR and spectral evolution

From the chemical evolution models calculated with the PEGASE code, we obtain the time-dependent star-formation rate, stellar mass, gas metallicity and spectral luminosity. We simulated several models corresponding to massive galaxies and chose two of them, the parameters of which, namely the SFR and the stellar mass, are close to those of the star-forming galaxies described by Tumlinson et al. (2011). With the accepted SFR law, \( SFR(t) = M^\Phi_i / p_i \), where \( M \) is the normalized mass of gas in \( M_\odot \) and throughout the article \( p_i = 2 \) is assumed, the notations are as in Fioc & Rocca-Volmerange (1997). In total we consider four models. The first two suggest a fixed normalization factor \( p_2 = 3 \times 10^3 \, Myr \, M_\odot^{-1} \) and two different values of the initial gaseous mass: \( M_2 = 2 \times 10^9 \, M_\odot \) (model A) and \( M_2 = 1.2 \times 10^{11} \, M_\odot \) (model C). The two others assume a fixed initial gaseous mass \( M_2 = 1.2 \times 10^{10} \, M_\odot \) and two different normalization constants \( p_2 \): one with \( p_2 = 3 \times 10^4 \, Myr \, M_\odot^{-1} \) (model D) and the other with \( p_2 = 5 \times 10^3 \, Myr \, M_\odot^{-1} \) (model E).

Fig. 1 presents the star formation rate, SFR, the specific star formation rate, sSFR = SFR/\( M_\star \), and the stellar mass, \( M_\star \), for model A (solid line), model D (dashed line) and model E (dashed–dotted line). Two features should be noted: first, the sSFR reveals differences between the models only after several hundred Myr and, secondly, models A and C show practically equal sSFR and as a result gas in these models is equally converted into stellar mass for models A (pentagons), C (circles), D (upward-pointing triangles) and E (downward-pointing triangles). Large filled symbols mark time moments shown nearby. Data for the star-forming and passive galaxies studied by Tumlinson et al. (2011) are depicted by small squares and rhomboids, correspondingly. The grey-scale map shows Sloan Digital Sky Survey (SDSS)+Galaxy Evolution
The cumulative ionizing background flux (thick grey line) at 3\text{PEGASE} r\sim2004= and \sim2004= and ionizing photons and the 100 kpc, which consists of the galactic (dashed line) and extragalactic (dotted line) ionizing photons. At low energies, E \lesssim 13.6 eV, the extragalactic contribution dominates at large distances, d \gtrsim 100 kpc, while the stellar population comes into play in UV range at smaller distances. Strong absorption of the galactic ionizing photons (E \sim 13.6–90 eV) in the galactic disc with fiducial N_{HI} and N_{HeI} values results in the total dependence of the ionic composition of halo gas on the extragalactic background. The significance of absorption by the galactic disc can be understood from comparison of the galactic spectral luminosity shown by the dash–dotted line and the cumulative flux (thick grey line).

A narrow bump at E \sim 90–136 eV is due to those galactic photons that survived against absorption in a thick disc. Its magnitude is obviously determined by our choice of neutral column densities N_{HI} and N_{HeI} in the disc. For the fiducial values of N_{HI} and N_{HeI}, the optical depth is about 3 for photons with E \sim 113 eV. Higher column densities can erase the bump and the extragalactic flux becomes dominant in the whole galactic halo. A decrease of the galactic contribution is also seen at larger distances from the galaxy, due to dilution r^{-2}. Note that the ionization potential of O \text{VI} (\lambda = 113.9 eV), falls exactly in the range E \sim 90–136 eV. This means that the fraction of O \text{VI} ions can increase in galaxies with lower column densities (N_{HI} and N_{HeI}) in their discs.

In general, the excess of galactic photons with energies higher than 113.9 eV contributes crucially to the ionization kinetics of the O \text{VI} ion. Fig. 4 presents the ratio of monochromatic galactic and extragalactic fluxes at 113.9 eV (solid lines) in model A for our fiducial column densities N_{HI} and N_{HeI}. It is clearly seen that the galactic flux dominates within r \lesssim 300 kpc at redshifts z \sim 0.2. At lower redshifts, the region of predominance of galactic flux widens, due mostly to a steep decrease of the extragalactic flux at these epochs. The monochromatic radiation at the H I Lyman limit is fully absorbed in the disc for the fiducial N_{HI} and N_{HeI} column densities.

In order to estimate both the escape of H I ionizing photons and the efficiency of O \text{V} ionization, we calculate the radial dependences of the ratios of ionizing fluxes Q_{HI}/Q_{HeI} and Q_{O VI}/Q_{O VI}, where

\begin{figure}[h!]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The dependence of the specific star formation rate on stellar mass for models A (pentagons), C (circles), D (upward-pointing triangles) and E (downward-pointing triangles). Large filled symbols mark time moments indicated in the figure. Data for star-forming and passive galaxies from Tumlinson et al. (2011) are depicted by small squares and rhomboids, correspondingly. The grey-scale map is for SDSS+GALEX galaxies (Schiminovich et al. 2007). SFR models are described in the text and in Fig. 1.}
\end{figure}

\begin{figure}[h!]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{The cumulative ionizing background flux (thick grey line) at z = 0.2 and at a distance from the galaxy d = 100 kpc, which consists of the UV and X-ray galactic spectrum, attenuated by galactic neutral gas (dashed line) and the extragalactic ionizing background (dotted line). The galactic spectral luminosity is shown by the dash–dotted line (right axis).}
\end{figure}

The dash–dotted line in Fig. 3 shows the galactic spectral luminosity at t = 7.5 Gyr, which is the time elapsed from z = 2 to 0.2. A significant break is clearly seen at wavelength 91 Å, which corresponds to the minimum wavelength in the spectrum reached in the PEGASE code. The break is due to an exponential decrease in the number of such hard photons emitted by the stellar population (see e.g. Rauch 2003), as they are only produced by very massive stars, the number of which is very small. As soon as we consider galactic evolution on time-scales longer than 1–3 Gyr, X-ray binaries are expected to have already formed; we extend the spectrum to higher energies assuming the empirical relation between X-ray luminosity and star-formation rate 'LX–SFR' (Gilfanov et al. 2004).

The thick grey line in Fig. 3 also shows an example of the total spectral radiation flux exposing a given gas parcel, located at distance d = 100 kpc from a galaxy evolved till z = 0.2. The total spectrum consists of the galactic (dashed line) and extragalactic (dotted line) ionizing photons. At low energies, E \lesssim 13.6 eV, the extragalactic contribution dominates at large distances, d \gtrsim 100 kpc, while the stellar population comes into play in UV range at smaller distances. Strong absorption of the galactic ionizing photons (E \sim 13.6–90 eV) in the galactic disc with fiducial N_{HI} and N_{HeI} values results in the total dependence of the ionic composition of halo gas on the extragalactic background. The significance of absorption by the galactic disc can be understood from comparison of the galactic spectral luminosity shown by the dash–dotted line and the cumulative flux (thick grey line).

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1\ The cut at 91 Å in the galactic spectral energy distribution (SED) generated by the stellar population codes (e.g. PEGASE, STARBURST99, GALAXEV) is apparently due to a choice of the developers and might be partly connected with the availability of spectral data in stellar libraries. The stellar library calculated by Rauch (2003) containing spectra up to 1 Å is not yet included in stellar population codes. It is also worth noting in this connection the considerable deviations of the spectral distribution above 228 Å predicted by different stellar population codes (Kewley et al. 2001). In this sense, our conclusions may depend on our choice of stellar population code and, particularly, on the cut at 91 Å. In Section 3.3, we discuss the stability of our results against possible variations of the galactic SED and the influence of the cut at 91 Å on the ionization and thermal evolution of the circumgalactic gas.
the superscripts ‘g’ and ‘e’ refer to the galactic and extragalactic contributions. Fig. 4 shows these ratios at \( z = 1.8 \) and 0.2 for model A. In the energy range \( E \gtrsim 113.9 \) eV, the galactic contribution dominates up to distance \( r \lesssim 200 \) kpc at \( z = 1.8 \) and extends even to \( r \lesssim 300 \) kpc at \( z = 0.2 \), due to a strong decrease of the extragalactic background at low redshifts. It is obvious that an increase of ionizing flux enlarges the radius of the zone of predominance of galactic ionizing photons: for instance, this zone increases from \( \sim 200 \) kpc in model A to \( \sim 300 \) kpc in model C at \( z = 1.8 \). A decrease of absorption in the disc also promotes growth of the zone of galactic predominance: it reaches \( r \gtrsim 250 \) kpc for \( N_{\text{HI}} \lesssim 10^{19} \) cm\(^{-2} \) even in model A.

### 3.2 Thermal and ionization evolution

Fig. 5 shows the evolution of temperature (lower panel) and O\( \text{VI} \) fraction (upper panel) in gas located at different distances from the galactic centre; here we assume the SFR as model A and our fiducial column densities \( N_{\text{HI}} \) and \( N_{\text{HeI}} \).

At the beginning, \( z \sim 2 \), oxygen is mainly locked in the O\( \text{VI} \) state due to high ionizing flux. Its fraction establishes around \( \sim 0.5 \) under the influence of the extragalactic ionizing background. After several hundred million years, the extragalactic background starts decreasing, following the cosmic star formation rate. This should result in a quick transition from O\( \text{VI} \) to O\( \text{I} \). In a cooling plasma, O\( \text{VI} \) recombines rapidly into lower ionization states and almost disappears shortly – a well-known O\( \text{I} \) ‘fragility’. However, in our case the excess of photons with \( E > 109.3 \) eV emitted by star-forming galaxies does not allow O\( \text{I} \) to recombine. Consequently, its fraction remains almost frozen at a level \( \sim 0.5 \) in the region \( d \lesssim 300 \) kpc over a range \( z \sim 1.2–0.2 \). In our models, \( f(O\text{VI}) \) reaches \( \sim 0.4–0.9 \) in low-metallicity (0.1 Z\( _{\odot} \)) gas within \( 50 < d < 150 \) kpc from \( z \sim 1–0 \). This value is several times higher than the maximum O\( \text{VI} \) fraction, \( \sim 0.1–0.2 \), reached in gas exposed only to the extragalactic background (e.g. Ferland et al. 1998; Gnat & Sternberg 2007) and in non-equilibrium collisional gas evolved from \( T = 10^{4} \) K (see e.g. Gnat & Sternberg 2007). Note that, even at large distances \( d \sim 250 \) kpc, \( f(O\text{VI}) \) remains higher than 0.1.

The temperature of gas with such a high O\( \text{VI} \) fraction is within \( (2–5) \times 10^{4} \) K (see lower panel in Fig. 5). The dependence of \( f(O\text{VI}) \) on metallicity is weak: for instance, the O\( \text{VI} \) fraction in gas with 0.01 Z\( _{\odot} \) is \( \sim 0.1–0.8 \) within distances \( 50 < d < 300 \) kpc in model A.

The cooling of gas with \( Z \lesssim 0.1 Z_{\odot} \) exposed only to the extragalactic background is due mainly to hydrogen and helium, whereas metals (oxygen and carbon) play a minor role in radiation losses (e.g. Wiersma, Schaye & Smith 2009; Vasiliev 2011). A considerable increase of O\( \text{VI} \) fraction in zones where galactic ionization dominates enhances the contribution of oxygen to cooling. As a result, gas temperature is lower in these regions, as seen in the lower panel in Fig. 5.

Deviation of column densities from the fiducial values accepted above may result in a considerable change of the overall picture, due to changes of the interrelation between the fractions of galactic and extragalactic ionizing photons. In order to understand how sensitive the oxygen ionization state is to the surface density of the underlying galactic gaseous discs, we calculate several models with different \( N_{\text{HI}} \) and \( N_{\text{HeI}} \). For simplicity, we assume that \( N_{\text{HI}}/N_{\text{HeI}} = 10 \).

Fig. 6 presents the galactic part of the spectrum at distance \( d = 100 \) kpc and redshift \( z = 0.1 \) for several values of \( N_{\text{HI}} \) (upper panel) and the evolution of the O\( \text{VI} \) fraction in gas exposed to this radiation field (lower panel). For column density \( N_{\text{HI}} = 10^{20} \) cm\(^{-2} \), the galactic spectrum in model A is fully absorbed in the range 13.6–80 eV. Only for a hundredth of this column density does the attenuation become less strong. A lower column density, \( N_{\text{HI}} \lesssim 10^{19} \) cm\(^{-2} \), allows a higher fraction of ionizing photons.
photon flux to the energy above the ionization potential of $O \, V$ (113 eV) penetrates into the halo and support a higher fraction of $O \, VI$ (lower panel); the $O \, VI$ fraction reaches $\sim$0.8–0.9 and increases slightly for lower column densities. This value is considerably higher than in collisionally ionized gas and in gas photoinized only by the extragalactic background. The reason for such a high fraction of $O \, VI$ is in the break at an energy slightly lower than the $O \, VI$ ionization potential (136 eV). It is worth noting that the uncertainty in the spectral energy distribution in this energy range within stellar population codes is rather high. This partly stems from the stellar atmosphere models and the rarity of extremely massive stars (Rauch 2003). On one hand, this is a shortcoming of our model, though on the other the rarity of massive stars and their short lifetime allows us to think that the stellar contribution to the circumgalactic ionizing field falls steeply at energies $E \gtrsim 125$–130 eV (see the spectra of the hottest stars in Rauch 2003), which is lower than the $O \, VI$ ionization potential (136 eV). However, it is important to note that the predominance of galactic flux over the extragalactic background in the range around 110–130 eV results in an $O \, VI$ fraction as high as 0.6–0.8. A higher $H \, I$ column density in underlying galactic discs, $N_{HI} \gtrsim$ several $\times 10^{20}$ cm$^{-2}$, heavily erases galactic flux in the range $E \sim 110$–130 eV, which, in Model A for instance, becomes lower than the extragalactic background and the effect of an enhanced $O \, VI$ fraction vanishes.

### 3.3 Stability against spectral variations at $\lesssim 91$ Å

It is obviously clear from the discussion in Section 3.2 that the enhanced $O \, VI$ fraction is due mainly to the excess of galactic photons with $E > 113$ eV in the bump at $E \sim 90$–136 eV. This bump maintains the $O \, VI$ fraction at a high level and keeps it against recombination to lower ionized states. The left border of this spectral feature, formed by too-strong absorption of galactic ionizing radiation in the disc, is irrelevant from the point of view of the maintenance of $O \, VI$ – even in the absence of any absorption, it remains enhanced (see Fig. 6). The right edge of the bump is, however, artificial in origin: as a matter of fact, the cut at 136 eV (91 Å) is a choice of the developers of stellar population codes (e.g. PEGASE, STARBURST99, GALAXEV). Therefore, in the following we discuss the convergence of our results against possible galactic spectral variations at energy higher than 136 eV.

Extreme ultraviolet and soft X-ray photons ($E \gtrsim 100$ eV) can be produced by post-asymptotic giant branch (post-AGB) stars before entering the white dwarf cooling phase (e.g. Werner et al. 1997). During this very bright evolution phase, lasting $\lesssim 10^7$ yr, the effective temperature may reach more than $T_e \sim 10^5$ K, while the surface gravity varies as $g \sim 10^{5.5} \times 10^6$ cm s$^{-2}$. Fig. 7 (upper panel) presents the two spectra for $T_e = 1.3 \times 10^5$ K and $1.5 \times 10^5$ K for solar metallicity taken from the stellar library (Rauch 2003). It is seen that the amount of photons with $E \gtrsim 136$ eV increases when the surface gravity $g$ decreases from $10^7$ to $10^5$ cm s$^{-2}$ for $T_e = 1.5 \times 10^5$ K. On the other hand, even a small decrease of effective temperature results in a shortage of photons with $E \gtrsim 125$ eV, independent of $g$. The majority of observed post-AGB stars are known to have masses below 0.6 M$_\odot$ and temperatures $T_e \sim 10^5$–1.5 $\times 10^5$ K (e.g. Werner et al. 1997), thus falling into the range shown here. For several spectra, a break around $E \sim 125$ eV is clearly seen. One can speculate that, in order to account conservatively for this break in the stellar population codes (e.g. PEGASE, STARBURST99), the value 136 eV (91 Å) was chosen as an upper limit of energy in their stellar library used in these codes. It is clearly seen, however, that even spectra with a break at $E \sim 125$ eV continue up to $E \sim 150$–170 eV and do not show such a strong decrease of flux at $E \gtrsim 136$ eV as is used in our calculations. One can speculate that this gradually decreasing flux above $E \sim 125$ eV produces qualitatively similar effects as does the flux with a break at $E \gtrsim 136$ eV.

In order to check this tentative conclusion, we performed calculations of ionization composition for several models of the ionizing flux above 136 eV; we construct several spectra and test the appearance of the enhanced $O \, VI$ fraction. We smooth the spectra calculated in the PEGASE code at energies $E \sim 100$–200 eV and match them at $E \gtrsim 200$ eV to the spectrum obtained from the 'Lx–SFR' relation as described in Section 2.3 (see Gilfanov et al. 2004). We proceed in such a manner that the resulting spectrum would be qualitatively close to the spectra depicted in the upper panel. Fig. 7 (middle panel) shows these spectra normalized using the spectral luminosity in model A. We calculate the ionization and thermal evolution of gas exposed to a cumulative spectrum that includes the extragalactic and the galactic radiation field. Fig. 7 (bottom panel) presents an example of the cumulative ionizing background flux at

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2 This is, up to now, the most complete library, which contains spectra up to 1 Å for hot compact stars.
a distance $d = 100$ kpc from the galaxy in models A, A+1...A+5 located at redshift $z = 0.2$ (thick lines). Fig. 8 shows evolution of the O VI fraction in gas exposed to an ionizing flux as in models A, A+1...A+5. It is readily seen that in all A+ models the O VI fraction is greater than 0.1 at redshifts $z \lesssim 0.2$. The O VI fraction is several times lower than in model A, but this is still obviously higher than $\lesssim 0.03$, which establishes itself in gas exposed only to extragalactic radiation (compare with the double-dotted line for log $N(H) = 20.5$ in the lower panel of Fig. 6). In models A+1 and A+2, oxygen at $z \gtrsim 1$ is mainly locked in O VII ions. Starting from $z \sim 1$, the ionization production rate of O VII ions decreases such that recombinations become efficient to replenish lower ionization states and, as a result, the fraction of O VII increases substantially at $z < 1$: from $\sim 0.03$ at $z = 1.5$ to 0.15 in A+1 and $\gtrsim 0.3$ in A+2 at $z \lesssim 0.2$. This balance between O VII and O VI is then kept quasi-steady down to $z \sim 0$. At large distances, the contribution from galactic photons decreases, resulting in a higher fraction of O VI in models A+1 and A+2. Note that, contrary to models A+1 and A+2, the flux in model A+5 is low and oxygen accumulates mostly in O IV-O V states.

Figure 8. The O VI fraction in gas at a distance $d = 100$ kpc from a galaxy exposed to the spectra corresponding to models A, A+1...A+5.

Higher galactic luminosities presented in the set of models C and C+3...C+5, result in a higher O VI fraction: $f(O\,VI) \gtrsim 0.5$ in gas located at $d = 100$ kpc at $z \lesssim 0.2$. However, in models C+1 and C+2 the ionization flux at $E \gtrsim 125$ eV is excessive and the fraction of O VI decreases to 0.03 and 0.07 at $z = 0.2$ and reaches only 0.05 and 0.1 at $z = 0$. At larger distances from a galaxy, where the flux drops, models C+1 and C+2 show an increase of O VI fraction: e.g. in model C+1 it increases to $\sim 0.07$ (0.11) at 150 kpc and $\sim 0.1$ (0.17) at 200 kpc at $z = 0.2$ ($z = 0$).

It is readily seen, therefore, that in the majority of these models the O VI fraction remains high and reaches $\gtrsim 0.2$ at a distance $d \gtrsim 100$ kpc from a galaxy located at $z \lesssim 0.2$. This is more than an order of magnitude higher than can be reached in gas exposed only to extragalactic radiation at $z \lesssim 0.2$. In model C+1, the O VI fraction reaches 0.1 only for $d \gtrsim 150$ kpc ($z \lesssim 0.2$), while at closer distances most oxygen is confined into O VII. It is worth stressing, however, that model C+1 can be considered as a model with an extreme possible contribution from post-AGB stars, in the sense that models with a higher spectrum are unlikely (e.g. Werner et al. 1997). Therefore, one can expect that, within conservative models of the galactic X-ray spectrum, the effect of enhanced O VI remains stable.
3.4 O VI in galactic haloes

In the previous section, we have found that the O VI fraction can reach high values of $f$(O VI) $\sim$ 0.4–0.9 under the action of ionizing radiation from the underlying galactic stellar population, along with the extragalactic radiation field. Such an O VI fraction is at least an order higher than the maximum \(~\sim 0.1\) reached in commonly used models with gas ionized collisionally and/or by extragalactic radiation. Assuming spherical symmetry and using the time-dependent O VI radial distribution around a host galaxy, one can find the O VI column densities along the line of sight crossing the galactic halo at impact parameter $b$. We integrate from $r = 50$ kpc to 300 kpc.

Fig. 9 (upper panel) presents the dependence of $N$(O VI) on impact parameter $b$ in a Z = 0.1 Z⊙ isochoric gas within models A and C. The O VI column density ranges from $N$(O VI) $\sim$ 10$^{14.9}$ to $\sim$10$^{15.7}$ cm$^{-2}$ at impact parameter $b \leq 200$ kpc, a factor of 3–10 higher than observed by Tumlinson et al. (2011). Therefore, circumgalactic gas of an order of magnitude lower metallicity, Z = 0.01 Z⊙, would provide good agreement with observations, as shown in Fig. 10 (upper panel). It is worth noting, however, that the spatial distribution of metals in the circumgalactic environment is highly non-homogeneous (e.g. Simcoe et al. 2006; Dedikov & Shchekinov 2004) and it is most likely that metals are locked in clumps of smaller covering factor, resulting in a proportionate decrease of the column density.

Fig. 9 (middle and lower panels) shows the column density of O VI in isobaric gas with initial density 10$^{-4}$ and 5 × 10$^{-5}$ cm$^{-3}$, respectively. The isobaric regime is supported by radiation losses and heating from ionizing radiation. Photo-heating grows at large distances from the galaxy, $r \gtrsim 250$ kpc, where the contribution from O VI ions to cooling decreases. At lower distances, the O VI fraction increases and becomes a dominant coolant, resulting in rather efficient cooling. Consequently, column densities grow under isobaric compression: $N$(O VI) can reach $\sim$10$^{15.5}$–15.9 cm$^{-2}$ for initial density 10$^{-4}$ cm$^{-3}$ and $\sim$10$^{15.6}$ cm$^{-2}$ for 5 × 10$^{-5}$ cm$^{-3}$. Similarly to the isochoric case, gas with lower metallicity (0.01 Z⊙) fits the observational data better.

Such high column densities are reached for galactic spectra with a cut at 91 Å (see footnote in Section 3.1). In reality, however, galactic spectra do not show such sharp breaks. In Section 3.3, we considered galactic spectra approximated smoothly around \(\sim 100–300\) eV to account for possible variations in the contribution from post-AGB stars. We have found that in the low-redshift range, $z \lesssim 0.2$, the O VI fraction in gas exposed to such approximated spectra remains sufficiently high in the majority of models considered here. In all cases, we have a considerable (order of magnitude) excess of the column densities calculated in models A and C with respect to the observed ones, as seen in Fig. 9.

Tumlinson et al. (2011) have argued that the circumgalactic medium can be a significant reservoir of the ejected material from galaxies. In order to explain the large column densities of O VI observed in the haloes, they have had to assume that the circumgalactic gas has nearly solar metallicity. This assumption meets difficulties, however, because the minimum oxygen mass in the halo obtained with such an assumption reaches around 10–70 percent of the total oxygen mass in the ISM (Tumlinson et al. 2011), in turn which requires unprecedented high mass exchange between the galactic ISM disc and a huge circumgalactic reservoir extending up to 150 kpc. The higher O VI fraction obtained in our model reduces the estimates to a more reasonable level and as a consequence weakens constraints on sources of oxygen in underlying galaxies.

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**Figure 9.** The dependence of the O VI column density on the impact parameter. Thin and thick lines correspond to models A and C (small symbols), respectively. Lines with filled symbols present the dependence for different redshifts (see details in the upper panel). The upper panel depicts the column density for isochoric (IC) gas with volumetric density $n = 10^{-4}$ cm$^{-3}$, while the middle and lower panels show the column density for the isobaric (IB) regime with initial density $n = 10^{-4}$ cm$^{-3}$ and $5 \times 10^{-5}$ cm$^{-3}$, respectively; the metallicity is 0.1 Z⊙. Open rhomboids and squares depict the observed column densities in passive and star-forming galaxies, respectively (Tumlinson et al. 2011); integration is over $r = 50–300$ kpc; different symbols correspond to different redshifts.
$I = I_\odot = E_{\text{N}}$ \textit{CLOUDY} and $12.5 - 13 \text{ cm}^2$ $\sim 2000$. The analysis of when collisions become significant compared with photoinionization is outside the scope of this article; details can be found in Vasiliev (2011).

3.5 O VI in galactic haloes: photoequilibrium

In extended galactic haloes, gas with a low density, $\sim 10^{-5} - 10^{-3} \text{ cm}^{-3}$, is exposed to rather a high ionizing background consisting of galactic and extragalactic components. Under such conditions the ionic state may reach photoequilibrium.\(^3\) Ionic composition under photoequilibrium is calculated by making use of \textit{CLOUDY}. We assume the time-dependent ionizing background described in Section 2.3. The difference between our calculations and the ones performed by Tumlinson et al. (2011) is that, besides the Haardt–Madau extragalactic radiation field used in (Tumlinson et al. 2011), we add the galactic contribution, which as we showed above may have crucial consequences: the excess of photons with $E \sim 13.6 - 130 \text{ eV}$ from the underlying stellar population competes with extragalactic radiation, while excess X-ray photons with $E > 113 \text{ eV}$ substantially enhance the O VI fraction (Section 3.2).

For the fiducial column densities $N_{\text{H}I} = 10^{20} \text{ cm}^{-2}$ and $N_{\text{He}I} = 10^{19} \text{ cm}^{-2}$, the O VI fraction in photoequilibrium is several magnitudes smaller than in our time-dependent models. In photoequilibrium, oxygen is mainly locked in less ionized states, O IV–O V, and O VI column density drops to $10^{12.5 - 13} \text{ cm}^{-2}$. When $N_{\text{H}I}$ and $N_{\text{He}I}$ decrease, the fraction of O VI instead increases. Even for $N_{\text{H}I} = 5 \times 10^{19} \text{ cm}^{-2}$ (here $N_{\text{H}I}/N_{\text{He}I} = 10$ is assumed), the O VI column density reaches $10^{14.2 - 14.7} \text{ cm}^{-2}$ at impact distances $b = 50 - 200 \text{ kpc}$ and $z = 0.1$. Further decrease of $N_{\text{H}I}$ results in the O VI fraction growing to $\sim 0.4 - 0.8$ and consequently higher O VI column densities.

Fig. 11 presents the dependence of the O VI column density on the impact parameter for a photoequilibrium model with $N_{\text{H}I} = 3 \times 10^{19} \text{ cm}^{-2}$ and a time-dependent model with $N_{\text{H}I} = 10^{20} \text{ cm}^{-2}$. The considerable difference between photoequilibrium and time-dependent models, which can be clearly seen, originates from the well-known fact that gas under non-equilibrium conditions is overionized with respect to what occurs under equilibrium (e.g. Gnat & Sternberg 2007; Suchkov & Shchekinov 1984; Vasiliev 2011). When $N_{\text{H}I}$ decreases, the absorption of galactic

\(^3\)The analysis of when collisions become significant compared with photoinionization is outside the scope of this article; details can be found in Vasiliev (2011).
ionizing radiation falls and the peak in the spectrum around $\sim$80–130 eV grows. In such conditions the photoionization time shortens, $t_p \sim \nu/\langle F, \sigma, \Delta \nu \rangle$, and the intrinsic photo-ionization ionization approaches photoequilibrium. At low $z$, the extragalactic flux decreases: for example, for $z = 0.1$, $F_\nu \sim 3 \times 10^{-24}$ erg cm$^{-2}$ Hz$^{-1}$ at $\sim$100 eV (Fig. 6). As a result, the photoionization time-scale $t_p$ of O VI ions increases up to several hundred Myr. Here $\sigma \sim 10^{-18}$ cm$^2$ and $\nu/\Delta \nu \sim 10$ are assumed; $\nu = 113.9$ eV is the O VI ionization potential and $\Delta \nu$ is the width of the peak in range 113–136 eV. This is several times shorter than the recombination time for gas with $n = 10^{-4}$ cm$^{-3}$, making non-equilibrium effects important.

Smaller absorption in the galactic disc provides higher galactic ionizing flux and shorter photoionization time-scale, such that the ion composition shifts to photoequilibrium. Thus, non-equilibrium effects are important for O VI ionization kinetics in the circumgalactic gas with $n \gtrsim 10^{-3}$ cm$^{-3}$ at $z \lesssim 0.5$. It can therefore be concluded that the main factor providing high O VI column densities in massive star-forming galaxies at low and moderate metallicities is the excess of photons with energies 113–130 eV from the stellar population of a host galaxy.

4 CONCLUSIONS

In this article, we have presented the photoequilibrium and non-equilibrium (time-dependent) ionization and thermal state of circumgalactic gas located at distances up to $\sim$50–300 kpc around star-forming galaxies and exposed to both extragalactic and galactic time-dependent ionizing backgrounds. For the extragalactic background, we considered the spectra obtained by Haardt & Madau (2001). Using the PEGASE code (Fioc & Rocca-Volmerange 1997), we have calculated the chemical and spectrophotometric evolution of galaxies and have chosen the two models with specific star formation rate (ssfr $= SFR/M_\star$) and stellar mass closest to the star-forming galaxies with large O VI column densities observed in Tumlinson et al. (2011).

We have found the following.

(i) The maximum O VI fraction can reach $\sim$0.4–0.9 under physical conditions (gas density and metallicity and spectrum shape) typical of those in the haloes of star-forming galaxies; such a high O VI fraction is due to galactic photons with $E \gtrsim 113$ eV; the effect of enhanced O VI remains stable within conservative models of galactic X-ray spectrum fluctuations at $E \sim 100$–200 eV.

(ii) Due to such a high fraction of O VI, its column density is in range $N(O\,\text{VI}) \sim 10^{13.9-15.7}$ cm$^{-2}$ even for low metallicity $Z = 0.1Z_\odot$ and $10^{14.5-15}$ cm$^{-2}$ for $Z = 0.01Z_\odot$ at impact parameters up to $\lesssim 200$ kpc; this results in a several times more conservative estimate of the oxygen mass in haloes, compared with $M_O = 1.2 \times 10^7(0.2/f_{\text{OVI}}) M_\odot$ (Tumlinson et al. 2011).

(iii) We have therefore shown that the large O VI column densities observed in the haloes of star-forming galaxies (Tumlinson et al. 2011) can be found in circumgalactic conditions with nearly 0.01–0.1 times solar metallicity and, correspondingly, the requirements for the sources of oxygen in extended haloes become reasonably conservative.

High O VI column densities in the haloes of star-forming galaxies can emerge under photoequilibrium as well as under nonequilibrium conditions. The main source is a high radiation flux of photons with $E \gtrsim 113$ eV from the stellar population of star-forming galaxies. Non-equilibrium effects for O VI ionization kinetics are important in the circumgalactic environment with $n \gtrsim 10^{-3}$ cm$^{-3}$ at $z \lesssim 0.5$.

Very recently, Lehner et al. (2014) have reported high O VI column densities in the circumgalactic medium at $z \sim 2$–3, with $N(O\,\text{VI})$ reaching $\sim 10^{16}$ cm$^{-2}$; the observational sample includes absorbers of different types, from Lyman-limit to damped Ly$\alpha$ systems. From our point of view, such a high O VI column density could be due to the excess of galactic ionizing photons with $E \sim 113$–135 eV over the extragalactic background, while the metallicity might be rather low.

ACKNOWLEDGEMENTS

We thank Jason Tumlinson for providing data and discussion and the anonymous referee for valuable comments and for pointing out a mistake. This work is supported by the RFBR through the grants 12-02-00365, 12-02-00917, 12-02-92704, and by the Russian Federal Task Program ‘Research and operations on priority directions of development of the science and technology complex of Russia for 2009–2013’ (state contracts 14.A18.21.1304, 2.5641.2011 and 14.A18.21.1179). EV is grateful for support from the ‘Dynasty’ foundation.

REFERENCES

Anderson M. E., Bregman J. N., 2010, ApJ, 714, 320
Asplund M., Grevesse N., Sauval A. J., 2005, in Barnes III T. G., Bash F. N., eds, ASP Conf. Ser. Vol. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis. Astron. Soc. Pac., San Francisco, p. 25
Bregman J. N. et al., 2009, Astro2010: The Astronomy and Astrophysics Decadal Survey, Science White Papers, No. 24, preprint (arXiv:0906.4984)
Brown P. N., Byrne G. D., Hindmarsh A. C., 1989, SIAM J. Sci. Stat. Comput., 10, 1038
Cowie L. L., Songaila A., Kim T.-S., Hu E. M., 1995, AJ, 109, 1522
Dedikov S. Yu., Shchekinov Yu. A., 2004, Astron. Rep., 48, 9
D’Odorico V., Celeri F., Cristiani S., Viel M., 2010, MNRAS, 401, 2715
Drake J. J., Testa P., 2005, Nat, 436, 525
Faucher-Giguère C.-A., Lidz A., Zaldarriaga M., Hernquist L., 2009, ApJ, 703, 1416

Figure 11. The dependence of O VI column density on the impact parameter for isochoric gas exposed to the ionizing spectrum in model A. In photoequilibrium, $N_{\text{HI}} = 3 \times 10^{20}$ cm$^{-2}$, whereas in the time-dependent model $N_{\text{HI}} = 10^{20}$ cm$^{-2}$ is adopted ($N_{\text{HI}}/N_{\text{HI}} = 10$ is assumed). Thin and thick lines correspond to non-equilibrium and photoequilibrium, respectively; density and metallicity are $n = 10^{-4}$ cm$^{-3}$ and $0.1Z_\odot$; other notation is as in Fig. 9.

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Feldmann R., Hooper D., Gnedin N. Y., 2013, ApJ, 763, 21
Ferland G. J., Korista K. T., Verner D. A., Ferguson J. W., Kingdon J. B.,
Verner E. M., 1998, PASP, 110, 761
Ferrara A., Pettini M., Shchekinov Yu. A., 2000, MNRAS, 319, 539
Ferland G. J., Korista K. T., Verner D. A., Ferguson J. W., Kingdon J. B.,
Verner E. M., 1998, PASP, 110, 761
Gnat O., Sternberg A., 2007, ApJS, 168, 213
Gnedin N. Y., Feldmann R., Hooper D., 2013, ApJ, 763, 21
Gnat O., Sternberg A., 2007, ApJS, 168, 213
Gnat O., Sternberg A., 2007, ApJS, 168, 213
Grcevich J., Putman M. E., 2009, ApJ, 696, 385
Gnedin N. Y., Feldmann R., Hooper D., 2013, ApJ, 763, 21
Haardt F., Madau P., 2001, in Neumann D. M., Tran J. T. V., eds, XXIst
Moriond Astrophys. Meeting, Clusters of Galaxies and the High Redshift
Universe Observed in X-ray Frontières, Paris, p. 64
Hammer F., Puech M., Chemin L., Flores H., Lehner M. D., 2007, ApJ,
662, 322
Izotov Yu. I., Thuan T. X., 1998, ApJ, 500, 188
Kewley L. J., Dopita M. A., Sutherland R. S., Heisler C. A., Trevena J.,
2001, ApJ, 556, 121
Koposov S. et al., 2008, ApJ, 686, 279
Lehner N., O’Meara J. M., Fox A. J., Howk J. C., Prochaska J. X., Burns
V., Armstrong A. A., 2014, ApJ, 788, 119
Pettini M., 1999, in Walsh J. R., Rosa M. R., eds, Proc. ESO Workshop
‘Chemical Evolution from Zero to High Redshift’. Springer-Verlag,
Berlin, p. 233
Prochaska J. X., Weiner B., Chen H.-W., Mulchaey J. S., Cooke K. L.,
2011, ApJ, 740, 91
Quilis V., Moore B., 2001, ApJ, 555, L95
Rauch T., 2003, A&A, 403, 709
Ryabova M. V., Shchekinov Yu. A., 2011, Astron. Rep., 55, 577
Salvadori S., Ferrara A., 2009, MNRAS, 395, L6
Savaglio S., 2009, in Cunha K., Spite M., Barbuy B., eds, IAU Symp No
265, Chemical Abundances in the Universe, p. 139
Schiminovich D. et al., 2007, ApJSS, 173, 315
Simcoe R. A., Sargent W. L. W., Rauch M., Becker G., 2006, ApJ, 637, 648
Stanimirović S., Dickey J. M., Krco M., Brooks A. M., 2002, ApJ, 576, 773
Steidel C. C. et al., 2010, ApJ, 717, 289
Suchkov A. A., Shchekinov Yu. A., 1984, Sov. Astron. Lett., 10, 13
Thomas D., Greggio L., Bender R., 1998, MNRAS, 296, 119
Tumlinson J. et al., 2011, Sci, 334, 948
Vasiliev E. O., 2011, MNRAS, 414, 3145
Weiner B. J., Williams T. B., 1996, AJ, 111, 1156
Werner K., Dreizler S., Heber U., Kappelmann N., Kruk J., Rauch T., Wolff
B., 1997, Rev. Mod. Astron., 10, 219
Wiersma R., Schaye J., Smith B. D., 2009, MNRAS, 393, 99

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