Where are the cosmic metals at $z \sim 3$?

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ABSTRACT

The global temperature distribution of the cosmic gas-phase oxygen at $z \sim 3$ is determined by combining high-resolution cosmological simulations of individual protogalactic as well as larger regions with the observed, extinction-corrected, rest-frame $V$-band galaxy luminosity function. The simulations have been performed with three different stellar initial mass functions (IMFs), a Kroupa (K98), a Salpeter (S) and an Arimoto–Yoshii (AY), spanning a range of a factor of 5 in chemical yield and specific supernova type II energy feedback. Gas-phase oxygen is binned according to $T$ as $\log(T) \lesssim 4.0$ ('cold'), $\log(T) \sim 4.5$ ('warm') and $\log(T) \sim 5.0, 5.5, 6.0, 6.5, 7.0$ ('hot' phases). Oxygen is found to be distributed over all $T$ phases, in particular for the top-heavy AY IMF. But, at variance with previous works, it is found that for the K98 and S IMFs the cold phase is the most important. For these IMFs it contains 47 and 37 per cent, respectively, of all gas-phase oxygen, mainly at fairly high density, $n_H \gtrsim 0.1$ cm$^{-3}$. The implications of this in relation to observational damped Ly$\alpha$ absorber studies are discussed. In relation to ‘missing metals’ it is found that a significant fraction of the oxygen is located in a warm/hot phase that may be very difficult to detect. Moreover, it is found that less than about 20–25 per cent of the cosmic oxygen is associated with galaxies brighter than $M_V \sim -22$, i.e. the faintest galaxy luminosities probed by current metallicity determinations for Lyman-break galaxies (LBGs). Hence, 75–80 per cent of the oxygen is also in this sense ‘missing’. From the LBG-based, $\lambda \sim 1500$ Å ultraviolet luminosity density history at $z \geq 3$, we obtain an essentially IMF-independent constraint on the mean oxygen density at $z = 3$. We compare this to what is obtained from our models, for the three different IMFs. We find that the K98 IMF is strongly excluded, as the chemical yield is simply too small, the Salpeter is marginally excluded, and the AY matches the constraint well. The K98 IMF can only match the data if the $\lambda \sim 1500$ Å extinction corrections have been overestimated by factor of $\sim 4$, which seems highly unlikely. The yields for K98 are also far too small to match the observational data for C IV. The optimal IMF should have a yield intermediate between the S and AY.

Key words: galaxies: evolution – galaxies: formation – cosmology: theory.

1 INTRODUCTION

A number of ‘problems’ have been discussed in relation to the cosmic mean metallicity and/or mean metal density. Pagel (1999) discussed the low redshift ($z \sim 0$) ‘excess metals problem’ showing that a comparison of the average metal to stellar densities in the low-$z$ Universe indicates that the average cosmic stellar initial mass function (IMF) has a higher yield, than what is obtained for the ‘standard’ Salpeter (1955) IMF. This is a well-known result for ellipticals in clusters (e.g. Romeo et al. 2006, and references therein), but Pagel’s analysis indicates that it could be more universal.

Conversely, Pettini (1999) formulated the high-$z$ ‘missing metals problem’ as follows. Studies of the comoving rest-frame ultraviolet (UV) luminosity density of high-$z$ Lyman-break galaxies (LBGs) allow us to trace the cosmic star formation density (or history, SFH), $\dot{\rho}_*(z)$, up to redshifts $z_{\text{max}} \approx 7–8$. Assuming an IMF of such stars, one can compute the specific fraction of heavy elements (‘metals’) they produce, $\gamma$, and derive the metal production rate $\dot{\rho}_Z(z) = \gamma \dot{\rho}_*(z)$. The integral from $z_{\text{max}}$ gives, at any given $z$, the density of cosmic metals $\rho_Z^{\text{SFH}}(z)$, or, expressed in units of the critical density, $\Omega_Z^{\text{SFH}}$. Moreover, if one restricts the analysis to elements, such as the $\alpha$ elements, produced almost exclusively in massive stars undergoing core collapse, the apparent dependence of $\rho_Z^{\text{SFH}}(z)$ on the IMF is essentially removed, since both the UV light and the oxygen production originate from massive stars. This will be discussed further.

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in Section 2, and was already noticed by, e.g. Songaila, Cowie & Lilly (1990), Madau et al. (1996), Pagel (1999) and Pettini (1999).

Early searches in cosmic structures for which the metal/baryon mass ratio (metallicity, \( Z = \Omega_Z/\Omega_h \)) can be derived either via intergalactic gas quasar absorption-line experiments [damped Ly\( \alpha \) absorbers (DLAs) or the Ly\( \alpha \) ‘forest’] or through direct spectroscopic studies of LBGs have found that only \( \Omega_Z^{DLA} < 0.02\Omega_\odot \) is stored in these components, i.e. the large majority of the metals are ‘missing’. Similar missing metal problems have been formulated by Wolfe, Gawiser & Prochaska (2003) and Prochaska et al. (2003, 2006) on the basis of star formation rates (SFRs) and metallicities of DLAs alone.

Ferrara, Scannapieco & Bergeron (2005, hereafter FSB05) attempted to quantify more precisely the extent of the missing metals deficit, and also to suggest where the ‘missing metals’ might be found. They found from considering typical stellar masses and metallicities of LBGs, and an estimate of the comoving density of LBGs a contribution of \( \Omega_Z^{LBG} = 3.4 \times 10^{-6} \) from LBGs. They also estimated the contribution from metals in DLAs to about \( \Omega_Z^{DLA} = 3.8 \times 10^{-7} \). Using the SFH estimate of Bouwens et al. (2004b), assuming a Salpeter IMF, and applying a dust correction factor of 4.5 (Reddy & Steidel 2004) they estimated that the Universe should be characterized by a total metallicity density of \( \Omega_Z^{SFH} = 1.84 \pm 0.34 \times 10^{-5} \) at \( z = 2.3 \). From the above numbers they concluded that about 80 per cent of the metals in the Universe are missing, in the sense that they are not directly associated with the above two galactic components.

FSB05 suggested that the ‘missing metals’ are associated with galaxies, mainly residing in their ‘hot’ gas haloes, having been deposited there by starburst-driven supernovae (see also Pettini 2004). This hypothesis seems reasonable, given that outflow velocities of 300–400 km s\(^{-1}\) are routinely inferred from the spectra of LBGs (e.g. Pettini et al. 2001; Shapley et al. 2003). Moreover, semi-analytical as well as fully hydrodynamical models of galaxy formation, based on cold dark matter (CDM), require such ‘feedback’ in order to enable the formation of realistic galaxies, solving the ‘over-cooling’, ‘angular momentum’, ‘missing satellites’ and other problems (e.g. Sommer-Larsen, Gelato & Vedel 1999; Cole et al. 2001; Thacker & Couchman 2001; Sommer-Larsen, Götz & Portinari 2003, hereafter SGP03).

Considering the widely used probes of Ly\( \alpha \) forest metal absorption in QSO spectra, C IV and O VI (e.g. Songaila 2001; Bergeron et al. 2002; Carswell, Schaye & Kim 2002; Boksenberg, Sargent & Rauch 2003; Schaye et al. 2003; Aracil et al. 2004; Simcoe, Sargent & Rauch 2004; Scannapieco et al. 2006; Bergeron & Herbert-Fort 2005; Tripp et al. 2006), FSB05 inferred observed integrated C IV and O VI column densities over the redshift range \( 1.7 < z < 3.8 \) and the corresponding cosmic average densities of these. Assuming a two-phase intergalactic medium (IGM), consisting of a ‘cold’ part \((T \sim 10^4 \text{ K})\) and a ‘hot’ part \((T \sim 10^7 \text{ K})\), responsible for the hydrogen Ly\( \alpha \) forest absorption, and a ‘hot’ component \((T \sim 10^6 \text{ K})\), they showed, using a number of simplifying assumptions, that more than 90 per cent of the metals can reside in the hot component, without violating the C IV and O VI Ly\( \alpha \) forest metallicity constraints (and with the cold phase as the major contributor to the C IV and O VI column densities). This result follows provided that \( T_{\text{hot}} \sim 10^8 \text{ K} \) and the density of the hot metal-enriched gas is only factors of a few times the mean cosmic baryonic density, which, e.g. at \( z = 3 \), corresponds to a hydrogen number density of \( n_H \sim 1.2 \times 10^{-3} \text{ cm}^{-3} \). FSB05 suggest this metal containing gas to be identified as wind-blown halo gas.

The low-luminosity galaxies at high redshift are traced by the DLAs (e.g. Fynbo et al. 1999; Haehnelt et al. 2000; Schaye 2001a; Møller et al. 2002). From very early on it was found that DLAs contain different regions with very different temperatures and ionization states (Turnshek et al. 1989). The DLA metal content discussed by FSB05 only accounts for the cold, mainly neutral component. The C IV and Si IV lines in DLAs corresponds to a warmer phase with more turbulent kinematics. The cross-section for strong C IV and Si IV absorption is much larger than for DLAs consistent with the picture that this gas is located in an extended wind-blown halo around the stellar components (Petitjean & Bergeron 1994, see also Adelberger et al. 2003, 2005; Porciani & Madau 2005; Scannapieco 2005). An even hotter component, traced by O VI and N V (temperatures of the order of \( 3 \times 10^7 \text{ K} \)), has recently been identified in DLAs (Fox et al. 2007). Fox et al. find that if the temperature of the O VI bearing gas is \( 10^6 \text{ K} \) or higher, then this hot phase can contribute significantly to the metal mass budget – qualitatively consistent with the proposal of FSB05.

Bouché et al. (2006a,b) discussed the missing metals problem at \( z \sim 2.2-2.5 \) and found that the problem is not quite as severe as at \( z \sim 3 \). Counting metal contributions from stars in BX galaxies (the equivalent of LBGs at \( z = 2.2 \)) e.g. Adelberger et al. (2004) and ‘distant red galaxies’ (see e.g. Franx et al. 2003; van Dokkum et al. 2003), as well as from gas in submillimetre galaxies (see e.g. Blain et al. 2004; Greve et al. 2005) and DLAs (e.g. Pettini et al. 2003) they could account for about 1/3 of the metals expected. The BX galaxies contain the largest fraction of the identified metals, about 55 per cent. Moreover, Bouché et al. (2007) found that another about 1/3 of the metals expected can be identified in the IGM at such redshifts.

Recently, Davé & Oppenheimer (2007, hereafter DO07) modelled the enrichment history of the Universe and address the missing metals problem using a fully numerical approach. They perform a moderate resolution cosmological hydro/gravity simulation of a cubic region of the Universe of 32 h\(^{-1}\) Mpc box size. Their simulation invokes metallicity and UV background-dependent radiative cooling, star formation and chemical evolution, in the instantaneous recycling approximation, and based on the Salpeter IMF. The simulation resolves galaxies of stellar masses down to \( \sim 10^7 \text{ M}_\odot \), corresponding to a V-band absolute magnitude \( M_V \sim -20 \) at \( z \sim 3 \). Due to the limited resolution, the authors adopt a parametrized description of starburst-driven outflows in the form of a ‘momentum-driven’ wind, found by Oppenheimer & Davé (2006, hereafter OD06) to yield the best match of the results of their simulations to various observational data.

DO07 quantify their results in terms of cosmic metal fractions in five phases: (i) stars, (ii) star-forming gas, (iii) halo gas (gas inside of the virial radius of galaxy haloes, which is not star forming), (iv) shocked IGM (gas outside of galaxy haloes of \( T \geq 3 \times 10^7 \text{ K} \)) and (v) diffuse IGM (gas outside of galaxy haloes of \( T < 3 \times 10^7 \text{ K} \)). At \( z \sim 3 \), they find that the dominant metal phase is the diffuse IGM, which contains about 40 per cent of the cosmic metals, with the other four phases containing approximately equal fractions of about 15 per cent. Hence, DO07 find that indeed only about 20 per cent of the metals in the \( z \sim 3 \) Universe reside in stars, while the ‘missing’ about 80 per cent are located in the gas phase. Moreover, they find that the hot halo gas is not the dominant, metal containing phase. Instead, a large fraction of the missing metals are ‘hidden’ in the diffuse IGM. DO07 suggest that this is possible, in relation to observations of, e.g. low-density IGM C IV abundances, because the diffuse gas is somewhat hotter than assumed in previous estimates, which at gas overdensities of \( \delta = \rho_{\text{gas}}/\rho_{\text{m}} = 1-100 \) implies larger C IV to C ionization corrections, and hence that larger amounts of C can be ‘hidden’ in this phase.
In this paper we take another approach from that of DO07 (see also Calura & Matteucci 2004, 2006). As we will show in the paper, due to resolution limitations DO07 likely fail to account for about half of the metals in the Universe produced by $z \sim 3$, on top of which adds cosmic variance effects, given the relatively small computational box of DO07. To undertake simulations of larger cosmological volumes, at the same time probing 8–10 mag deeper (Section 5) is at present, as well as in any foreseeable future, computationally prohibitive. Using K-band observations of a sample of LBGs, Shapley et al. (2001) determined the $z \sim 3$ rest-frame V-band galaxy luminosity function (LF). In Sommer-Larsen & Fynbo (in preparation, hereafter Paper I) we correct the Shapley et al. LF for extinction and other effects, to obtain a ‘true’ $z \sim 3$ LBG LF. Subsequently, cosmological high-resolution hydro/gravity simulations of the formation and evolution of individual galaxies are combined with the corrected galaxy LF to obtain estimates of the average cosmic density of metals (in particular oxygen) residing in stars at $z = 3$. We consider models based on three different stellar IMFs, spanning almost a factor of 5 in chemical yield as well as thermal/kinetic energy feedback from supernova type II (SNII) explosions. These are the Kroupa (1998, K98) IMF, a typical IMF suited for chemical evolution models of the solar neighbourhood, e.g. Boissier & Prantzos (1999), the ‘standard’ Salpeter (1955, S) IMF and the Arimoto & Yoshii (1987, AY) IMF, which is well suited for describing the chemical evolution of elliptical galaxies. The simulations have sufficiently high resolution to allow a two-phase modelling of the star-forming interstellar medium (ISM), consisting of a ‘cold’ $T \sim 10^4$ K star-forming phase and a ‘hot’ $T \sim 10^5$–$10^6$ K phase, intermixed with the cold gas. Starbursts drive galactic winds by depositing thermal energy from multiple SNII explosions in the gas, part of which is subsequently converted into kinetic energy self-consistently by the hydro code.

In Paper I we conclude that for none of the IMFs it is possible to reconcile the amount of oxygen locked in stars with the amount predicted from the (observed) cosmic UV luminosity density history, hence confirming the ‘missing metals problem’ as stated by Pettini (1999) and FSB05.

In this paper we combine the high-resolution galaxy formation models with the V-band LF to determine the cosmologically averaged amount and properties of $z = 3$ gas-phase metals, mostly focusing on oxygen, but also on carbon, in particular in relation to QSO absorption-line determinations of the cosmic CIV density, as well as iron, in relation to DLA abundances. Combining the results obtained with those of Paper I the total cosmic metal distribution is obtained for the three IMFs considered. Comparing in turn these results to inferences from the observed cosmic UV luminosity density history allows us to significantly constrain the ‘true’ cosmic stellar IMF. Finally, relations to the ‘missing metals problem’, as well as results obtained by other authors, are discussed.

The paper is organized as follows. In Section 2 we derive constraints on cosmic metal production from the cosmic UV luminosity density history, in Section 3 we briefly describe the hydro/gravity galaxy formation simulations, and in Sections 4 and 5 we present the approach used in this paper to determine the temperature distribution of the cosmic gas-phase metals. Section 6 presents results on gas-phase CIV abundances, and, relating these to observations of CIV absorption lines in QSO spectra, we derive a constraint on the cosmic IMF. In Section 7 we combine the results of Paper I and those obtained here to derive the total cosmic metal distribution. Comparing this to what is obtained from the cosmic UV luminosity density history we obtain an additional constraint on the cosmic stellar IMF. In Section 8 we relate our results to the ‘missing metals problem’ and compare them to those of other workers in the field, in Section 9 we demonstrate that our results are robust to changes of the numerical resolution and, finally, Section 10 summarizes our conclusions.

In the paper we assume the flat Λ cosmology, with $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$ and $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$, with $h = 0.7$, unless it is explicitly stated otherwise.

## 2 Constraints on metal production from the cosmic UV luminosity density history

Constraints on metal production from the cosmic UV luminosity density history are discussed in Paper I, but for coherence we present the main discussion in the following as well.

The luminosity of young galaxies at rest-frame $\lambda \sim 1500$ Å is a measure of the rate of formation of massive stars (mainly O and B type) as shown by e.g. Madau, Pozzetti & Dickinson (1998). Moreover, α elements like oxygen are almost exclusively produced in such massive stars, and hence there is a direct link between the cosmic average oxygen production rate density and the average UV luminosity density, which is essentially independent of the stellar IMF – see e.g. Pettini (1999). To estimate the cosmic oxygen production rate density as a function of redshift we use various recent estimates of the average cosmic SFR. The estimates have been obtained from Steidel et al. (1999), Bouwens et al. (2004a,b), Bunker et al. (2004), Giavalisco et al. (2004), Schiminovich et al. (2006) and Sawicki & Thompson (2006). The estimates used are all based on assuming a ‘standard’ Salpeter IMF in converting from UV luminosity to SFR. The oxygen (mass) yield of a Salpeter IMF is 0.01 (e.g. Lia, Portinari & Carraro 2002a,b) – hence in Fig. 1 we have multiplied the published SFRs by 0.01 to obtain the (essentially) IMF-independent oxygen production rate densities. The estimates have moreover been corrected to correspond to (at any redshift) the UV luminosity density of galaxies brighter than $0.1 \times L^*_{UV, z = 3}$ following an approach similar to that of Bouwens et al. (2006); note though that the $z \sim 7.5$ data point of Bouwens et al. 2004b only

![Figure 1. Cosmic oxygen enrichment history based on observations of high-z LBGs. The data points shown are based on Steidel et al. (1999; green crosses), Schiminovich et al. (2005; open red dot), Sawicki & Thompson (2006; open blue dots), Giavalisco et al. (2004; black squares), Bunker et al. (2004; blue square), Bouwens et al. (2004a; magenta triangle), Bouwens et al. (2006; magenta circle), Bouwens et al. (2004b; magenta pentagon – note that the latter only represents $L \geq 0.3 \times L^*_{UV, z = 3}$). The ‘maximum’ model is shown by the upper short-dashed curve, the ‘median’ model by the long-dashed curve, and the ‘minimum’ model by the lower short-dashed curve.](https://academic.oup.com/mnras/article-abstract/385/1/3/1028960)
represents $L \geq 0.3 \times L_{UV}(z=3)$. Finally, the values shown in the plot result from multiplying the observed values by a dust-correction factor of 5.5. This value is intermediate between the $z \sim 3$ values of 4.5 and 6.5 suggested by Reddy & Steidel (2004) and Dahlen et al. (2007), respectively (but see below).

The cosmic average oxygen density at $z = 3$ can now be obtained by integrating the oxygen production rate density, $\rho_O(z)$, from $z = 3$ and back in time. We shall consider three models for $\rho_O(z)$: the ‘median’ model, the ‘maximum’ model, and the ‘minimum’ model. The median model is obtained by calculating the median values of $\rho_O(z)$ in the bins $z = 3-4$ and $z = 4-6$ (assigning equal weight to each data point, but excluding the $z = 5.9$ value of Bunker et al. 2004; see below), and connecting these values with the $z \simeq 7.5$ value of Bouwens et al. (2004b). This model is shown in Fig. 1 by the long-dashed curve. The maximum model is obtained by connecting the $z = 3-4$ median value with the Giavalisco et al. (2004) $z \simeq 5.7$ value, and the Bouwens et al. (2004b) $z \simeq 6.0$ value, and multiplying the resulting ‘upper envelope’ by a factor of 6.5/5.5 to maximize also the dust correction. This model is shown by the upper short-dashed curve in Fig. 1. Finally, the minimum model is obtained by connecting the $z = 3-4$ median value with the Giavalisco et al. (2004) $z \simeq 4.8$ value, the Bouwens et al. (2004a) value and the Bouwens et al. (2006) $z \simeq 7.5$ value, and multiplying this ‘lower envelope’ by a factor of 4.5/5.5 to minimize the dust correction (but see below). This model is shown by the lower short-dashed curve in Fig. 1.

Assuming a flat space world model, the $z = 3$ cosmic average oxygen density can now be evaluated as

$$\rho_O(z = 3) = -\int_{t(z=3)}^{\infty} \rho_O(t) \, dt \frac{\rho_O(z)}{(1+z)^{-1} \Omega_\Lambda} - (2+z) \Omega_\Lambda \, dz,$$

where values of $H_0 = 100 \, h \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, with $h = 0.7$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ are assumed in this paper. Using equation (1) we obtain $\rho_O(z = 3) = 0.32, 0.42$ and $0.56 \times 10^7 M_\odot/(h^{-1} \, \text{Mpc})^3$ for the ‘minimum’, ‘medium’ and ‘maximum’ models, respectively. These numbers represent an integral constraint that any successful model of galaxy formation must meet. As will be shown in Section 5 this enables us to strongly constrain the ‘cosmic’ stellar IMF at $z \geq 3$.

In determining the ‘median’ and ‘minimum’ models we excluded the $z = 5.9$ value of Bunker et al. (2004). This is simply done on the basis of the large discrepancy between this value, and all other $z = 4-6$ values. To indicate the effect of this, we determined an alternative median model in which the Bunker et al. (2004) value is included in the $z = 4-6$ bin. This changed the median model estimate of $\rho_O(z = 3)$ from 0.42 to 0.40 and $0.56 \times 10^7 M_\odot/(h^{-1} \, \text{Mpc})^3$, i.e. a $\sim 2$ per cent change, and hence quite small effect, which, given all other uncertainties, we shall ignore in the following.

Bouwens et al. (2006) propose that the $\lambda \sim 1350-1500$ Å extinction correction decreases with increasing $z$ from $z \simeq 3$. Converting their proposed, extinction-corrected SFR$(z)$ to a corresponding $\rho_O(z)$ (including changing the UV luminosity density from their limit of $0.04 \times L_{UV}(z=3)$ to the limit of $0.1 \times L_{UV}(z=3)$ used here) results in a value of $\rho_O(z = 3) = 0.33 \times 10^7 M_\odot/(h^{-1} \, \text{Mpc})^3$, hence within the bounds derived above.

The integral constraint obtained in this section can also be expressed in units of the critical density: we obtain $\Omega_\rho(z = 3) = \rho_O(z = 3)/\rho_{cr} = 0.81, 1.05$ and $1.41 \times 10^{-5}$ for the minimum, median and maximum models, respectively.

FSB05 obtained for the total density of heavy elements in units of the critical $\Omega_\rho = (1.84 \pm 0.34) \times 10^{-5}$, by integrating the observed cosmic SFH (based on a Salpeter IMF), as presented by Bouwens et al. (2004b), to $z = 2.3$ and applying a dust correction factor of 4.5. The above value translates into $\Omega_\rho(z = 2.3) = (0.77 \pm 0.14) \times 10^{-5}$. If the oxygen density production rate models shown in Fig. 1 are continued $z = 2.3$, we would obtain 1.22, 1.55 and 2.01 $\times 10^{-5}$. The reason for the apparent discrepancy is twofold: (i) we use a dust correction of a factor of 5.5 and (ii) more importantly, the Bouwens et al. (2004b) SFH was based on a UV luminosity to a limit of $0.3 \times L_{UV}(z=3)$, rather than the limit of $0.1 \times L_{UV}(z=3)$ adopted in this work. Using the $z \sim 3$ UV LF of Adelberger & Steidel (2000) we estimate the latter correction to be a factor of 1.5. Multiplying this by a factor of 5.5/4.5 the findings of FSB05 would translate into about $(1.4 \pm 0.3) \times 10^{-5}$, in good agreement with our values above.

Extremely dust-observed galaxies such as high-z Submillimetre Common-User Bolometer Array (SCUBA) sources (e.g. Smail, Ivison & Blain 1997; Barger et al. 1998; Eales et al. 1999; Chapman et al. 2005) are not included in the dust-corrected SFR densities shown in Fig. 1. Most such galaxies have UV luminosities that heavily under-represent their SFRs and thus such galaxies are not properly included in the estimate of the oxygen production rate density. Their numbers may be sufficiently large that their contribution is significant; however, we neglect this contribution for two reasons: (i) the contribution from such galaxies would be largest at $z \sim 2$, where the redshift distribution of SCUBA sources appears to peak (Chapman et al. 2005; Reddy et al. 2005), whereas we are concerned with the range $z \gtrsim 3$ and (ii) more importantly, we are concerned with the oxygen production rate density history of LBGs only, as we wish to compare the integral constraint thus obtained to results of combining the observed LBG $z \sim 3$ optical rest-frame LF with detailed, high-resolution models of galaxy formation.

3 THE SIMULATIONS

The code used for the simulations is a significantly improved version of the TREEPSH code we used for our previous work on galaxy formation (SGP03). A similar version of the code has been used recently to simulate clusters of galaxies, and a detailed description can be found in Romeo et al. (2006). Here we briefly mention its main features and the upgrades over the previous version of SGP03 – see also Sommer-Larsen (2006).

(i) The basic equations are integrated by incorporating the ‘conservative’ entropy equation solving scheme of Springel & Hernquist (2002), which improves the numerical accuracy in lower resolution regions.

(ii) Cold high-density gas is turned into stars in a probabilistic way as described in SGP03. In a star formation event an SPH particle is converted fully into a star particle. Non-instantaneous recycling of gas and heavy elements is described through probabilistic ‘decay’ of star particles back to SPH particles as discussed by Lia et al. (2002a). In a decay event a star particle is converted fully into an SPH particle, so that the number of baryonic particles in the simulation is conserved.

(iii) Non-instantaneous chemical evolution tracing 10 elements (H, He, C, N, O, Mg, Si, S, Ca and Fe) has been incorporated in the code following Lia et al. (2002a,b); the algorithm includes SNII and SNIa, and mass-loss and chemical enrichment from stars of all masses. Most of the simulations presented in this paper have been undertaken using three different IMFs: the Kroupa (1998) IMF (denoted K98 in the following), derived for field stars in the solar 

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neighbourhood, the standard Salpeter IMF (S), and the more top-heavy Arimoto & Yoshii (1987) IMF (AY), which is well suited for the modelling of elliptical galaxies, as well as galaxy clusters. More detail is given in Lia et al. (2002a,b).

(iv) Atomic radiative cooling is implemented, depending both on the metallicity of the gas (Sutherland & Dopita 1993) and on the metagalactic UV field, modelled after Haardt & Madau (1996). Moreover, a simplified treatment of radiative transfer, switching off the UV field where the gas becomes optically thick to Lyman-limit photons on scales of ~1 kpc, is invoked.

(v) Starburst-driven winds are incorporated in the simulations at early epochs (z ≥ 5–6), as strong early feedback is crucial to largely overcome the angular momentum problem (SGP03). A burst of star formation is modelled in the same way as in SGP03: when a star particle is formed, further self-propagating star formation is triggered in the surroundings; the energy from the resulting, correlated SNII explosions is released initially into the ISM as thermal energy, and gas cooling is locally halted to reproduce the adiabatic supershell expansion phase; a fraction of the supplied energy is subsequently converted (by the hydro code itself) into kinetic energy of the resulting expanding superwinds and/or shells. The supershell expansion also drives the dispersion of the metals produced by SNII [while metals produced on longer time-scales are restituted to the gaseous phase by the ‘decay’ of the corresponding star particles, see point (ii) above].

At later epochs, only a fraction (typically, 20 per cent) of the stars induce efficient feedback, and star formation is no longer self-propagating so that no strong starbursts are triggered by correlated SN explosions. This allows the smooth settling of the disc (see SGP03 for all details). Star formation efficiencies have been chosen such that realistic disc galaxy gas fractions result at z = 0 (SGP03), and can also be shown to match the Kennicutt (1998) star formation relation quite well.

AGN driven feedback has not been invoked in the simulations, as it is unlikely to play a major role in the formation of, at least, disc galaxies (e.g. Sommer-Larsen 2006) – the most common galaxy type in the Universe. The higher stellar UV escape fractions as well as LyC luminosities found by Razoumov & Sommer-Larsen (2007) at z = 3.6, compared to z = 3, also support the notion that massive stars in galaxies become progressively more important sources of ionizing photons as one goes back in time, as the comoving number density of quasars declines rapidly at z ≥ 3 (e.g. Richards et al. 2006). This provides additional circumstantial evidence that AGN feedback is of minor importance, at least at z ≥ 3, the relevant redshift range in this paper.

The galaxies were drawn and resimulated from a 10$h^{-1}$ Mpc box-length dark matter (DM)-only cosmological simulation, based on the ‘standard’ flat ΛCDM cosmological model ($h = 0.65, Ω_0 = 0.3, σ_8 = 1.0$); our choice of $h$ and $σ_8$ is slightly different from presently more popular values (0.7 and 0.9, respectively), but this has little impact on the resulting galaxy properties (e.g. Portinari & Sommer-Larsen 2007). When resimulating with the hydro code, baryonic particles were ‘added’ to the original DM ones, which were split according to an adopted baryon fraction $f_b = 0.15$. The gravity softening lengths were fixed in physical coordinates from z = 6 to 0 and in comoving coordinates at earlier times.

The simulations are run with resolutions of $m_{SPH} = m_*=3.6 \times 10^7, 4.5 \times 10^7 M_\odot, r_{DM,DM} = 2.0 \times 10^7, 3.3 \times 10^7 M_\odot$ and $ε_{SPH} = ε_s = 0.08–3.8$ kpc going from the smallest individual galaxy simulations to the largest protocluster simulation. Each region containing an individual protogalaxy was simulated using 0.2–2.2 million particles in total; in addition two ‘low’ and ‘medium’ galaxy density regions were simulated using 1.4 and 1.6 million particles, a protocluster region using 1.4 million particles, and a protocluster region using 2.3 million particles (the high-resolution ‘Virgo’ simulation of Romeo et al. 2006).

Images of some of the simulated galaxies are available at http://www.tac.dk/~jsalarsen.

4 THE APPROACH

The approach adopted is, based on the simulations, to characterize a given galaxy at $z = 3$ and of absolute magnitude $M_V$ by a distribution of ISM/IGM oxygen mass $m_0(V_*, log(T))$, where $log(T) = 3.5, 4, 4.5, \ldots, 7$, and a given value of $log(T)$ corresponds to gas temperatures in the range $T = [10^{log(T)−0.25}, 10^{log(T)+0.25}] \,K$. Almost no oxygen is found at temperatures lower than $10^{5.5} \,K$, mainly because the radiative cooling function is effectively truncated below about 8000 K. If molecule formation and molecular cooling had been invoked in the hydro/gravity simulations, part of this gas would have formed in a much colder, high-density, predominantly H₂ phase (see also Section 8.1). Moreover, it is found that the $log(T) = 3.5$ as well as 4 ISM/IGM oxygen is spatially associated with the stellar galaxies (similar spatial extents), so the $log(T) = 3.5$ and 4 bins have been merged, and are denoted by $log(T) = 4$. Hence, all gas colder than $10^4 \,K$ is included in this phase. Moreover, for field galaxies at $z ≥ 3$ almost no oxygen is found in the $log(T) > 7$ phases, which will therefore be ignored in the following.

Once the functions $m_0(V_*, log(T))$ have been determined for a given IMF, the cosmologically averaged (gaseous) oxygen temperature distribution can be determined by folding these functions with the (dust corrected) rest-frame V-band LF at $z = 3$. We stress that $m_0(V_*, log(T))$ pertains only to the galaxy itself, not including any of its satellite galaxies – see further below.

To determine $m_0(V_*, log(T))$ we proceed as follows: in Fig. 2 (left-hand panel) is shown the cumulative mass of ISM/IGM oxygen, $M_V(r_*, log(T))$, around three (mostly) isolated galaxies of $M_V = −16.1, −21.4$ and −25.3, respectively, simulated using the K98 IMF. Fig. 2 (right-hand panel) is similar, but for the same three galaxies, of $M_V = −13.8, −19.3$ and −25.4, simulated with the AY IMF. For all three galaxies the region from $r_{vir}$ to 8 $r_{vir}$ is shown, and the different curves correspond to $log(T) = 4, 4.5, \ldots, 7$. As can be seen from the figure, for a given galaxy and $log(T)$, the cumulative gas oxygen mass gently increases with $r$ by factors of ~1.5–4, over the radial range shown. The one exception is the $log(T) = 4$ case, where the gas metals are mainly spatially correlated with the central galaxies, and the curves are quite flat (with the exception of the very bright galaxy, which has been selected from the protocluster simulations). We stress that the mass of gas-phase oxygen around a given (isolated) galaxy has been contributed not only by the stars in the galaxy itself, but also by stars in all its satellite galaxies (and in principle also by ‘intergalactic’ stars, as will be discussed below).

We select a sample of ‘base’ galaxies consisting of (mainly) isolated galaxies ranging in absolute V-band magnitude from about −12 to −25. It is assumed that in order to account for the $m_0(V_*, log(T))$ of a given base galaxy one should include all gas oxygen

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1 In this paper the virial radius, $r_{vir}$, is the radius corresponding to, at $z ≥ 3$, an overdensity 181 times the mean matter density of the Universe at this redshift, as appropriate for a top-hat collapse in the adopted ΛCDM cosmology (e.g. Bryan & Norman 1998).
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M8. For the brightest galaxies, V

tain values of log(T)

creasing T (depending on the IMF) galaxies are found to

be isolated, such that, even for isolated galaxies, with in-

creasing T increasing amounts of gas-phase oxygen associated with

and (ii) for cer-

tain values of log(T) (depending on the IMF) galaxies are found to

‘share’ a common pool of gas-phase oxygen. In practice it is found

that for none of the IMFs considered, and any log(T), does T exceed

8. For the brightest galaxies, MV ≤ −23, T does not exceed 4.

Fig. 4 shows, for log(T) = 4.5, 5, 5.5 and 6, the spatial distribution

of the gas-phase oxygen for a region containing 52 resolved galaxies

with MV in the range −15 to −22.5, simulated using the K98 IMF.

Each dot represents, for a given log(T), an equal amount of gas-

phase oxygen mass, so the figure displays the actual distribution of
gas-phase oxygen mass, not gas mass. As can be seen, the spatial

oxygen mass distributions depend strongly on the gas temperature.

In Fig. 5, is shown, for the three IMFs considered, the distribu-
tion of log(T) = 6 oxygen mass. As can be seen, the oxygen mass

distribution also depends strongly on the IMF adopted. For compar-

ison is also shown the corresponding plot for a K98 simulation of a

proto-elliptical, high-density region, which is biased towards many

large galaxies (bottom left-hand panel) It is seen how the log(T) = 6

oxygen mass distribution in this case is concentrated near the large
galaxies, more so than for the more representative ‘field’ galaxy

case.

We now approximate T(MV, log(T)) by T(log(T)), i.e. independ-

ent of MV. We show further below that this is a good approximation,

except for the very brightest galaxies, for which a correction has to

be made. For each IMF, T(log(T)) is determined as follows. (i) For a

number of regions containing up to about 200 resolved galaxies we

(1) determine the absolute V-band magnitudes of the N galaxies in

the region, MV, ..., MV,N and (2) the total gas-phase oxygen mass

temperature distribution of the region

\[ f_{\text{O, region}}^{\text{overall}}(\log(T)) = \int_{\text{region}} \rho_{\text{O}}(\bar{x}; \log(T)) \, d\bar{x}. \]

(ii) For a given set of base galaxies, and given values of T(log(T)), one can predict the total mass of oxygen as a function of log(T) as

\[ f_{\text{O, region}}^{\text{predicted}}(\log(T)) = \Sigma_{i=1}^{N} M_{\text{O}}^{\text{predicted}}(\bar{r} \times r_{\text{vir}}(M_{V, i}); \bar{r} \times r_{\text{vir}}(M_{V, i}); \log(T)). \]

where \( M_{\text{O}}^{\text{predicted}}(\bar{r} \times r_{\text{vir}}(M_{V, i}); \log(T)) \) is determined by linear inter-

polation in MV as well as T(log(T)) as T(0, 1, ..., 8) using the corre-

sponding values for the base galaxies. The values of T(log(T)) are

then obtained such as to provide the best simultaneous match of f_{\text{O, region}}^{\text{predicted}}(\log(T)) to f_{\text{O, region}}^{\text{overall}}(\log(T)) for a number of simulated

regions, using standard least-squares fitting.

For all three IMFs this is done for the same two regions, represent-

ing ‘low-density’ and ‘medium-density’ ‘field’ environments, with
galaxies of MV ≥ −22.5. The two regions are simulated using a
total of 1.4 and 1.6 million particles, respectively. For the AY IMF,
Where are the cosmic metals?

Figure 4. Spatial (projected) distributions of gas-phase oxygen in the ‘medium-density’ field galaxy region, at $z = 3$, for the K98 simulation. Results for five different temperature bins, corresponding to $\log(T) = 4, 4.5, \ldots, 6$, are shown. All temperature bins are represented using about 5000 ‘dots’, which for each temperature bin correspond to equal amounts of oxygen mass. Hence, each figure illustrates directly the spatial distribution of the gas-phase oxygen mass, not gas mass. The cold-phase ($\log(T) = 4$) is shown by red dots in all four figures. In addition the $\log(T) = 4.5, 5, 5.5$ and 6 phases are shown by blue dots in the corresponding panels.

The predicted distribution falls somewhat short of the actual one in the $\log(T) = 4, 4.5$ and 5 temperature bins. This implies that the results obtained in the following section for the faintest galaxies are actually lower limits. Given the small magnitude of the effect we shall, however, neglect this in the following.

In Fig. 7 a similar comparison is shown for AY IMF simulations. Again, the match between predicted and actual distributions is, in general, good. For the smallest galaxies the distributions are somewhat different (see above). For the protocluster region, the predicted distribution exceeds the actual one, with $f_{\text{predicted}}^{\Omega_{\text{region}}}(\log(T))$ being up to about twice as large as $f_{\text{actual}}^{\Omega_{\text{region}}}(\log(T))$. This is due to the very large galaxy density in such environments. Using this region to solve for an alternative set of $\tilde{r}(\log(T))$ results in $\tilde{r}(\log(T))$ values of about half the ones obtained as described above. As the main contribution to $f_{\text{actual}}^{\Omega_{\text{region}}}(\log(T))$ is associated with the larger galaxies in the region, $M_V \sim -24$ to $-25.5$, $f_{\text{actual}}^{\Omega_{\text{region}}}(\log(T))$ in all regions can be matched by a model, where $\tilde{r}(\log(T))$ changes linearly from the ‘field’ values to the ‘protocluster’ values between $M_V = -22$ and $-24$, as shown in Fig. 6. However, in any case this correction
for the very large galaxies is of no consequence to the main results presented in the following section. This is because the contribution from such galaxies to the overall cosmic metal budget is very minor, as will be detailed in the following section.

Finally we note, that even in typical ‘field’ environments, some fraction of the stellar systems originally formed have subsequently been disrupted through tidal stripping and other dynamical processes. The gas-phase metals produced by these ‘intergalactic’ stars are ‘automatically’ accounted for by the above approach, but in any case the fraction of such stars is quite small, $\lesssim 5\text{–}10$ per cent (Paper I).

5 THE TEMPERATURE DISTRIBUTION OF THE COSMIC GAS-PHASE OXYGEN

The average cosmic density of gas-phase oxygen at $z = 3$, as a function of gas temperature, can now be obtained as

$$
\langle \rho_0(\log(T)) \rangle = \int_0^\infty \frac{dN(L_V)}{dL_V} m_0(M_V(L_V), \log(T)) dL_V,
$$

where $dN(L_V)/dL_V$ is the rest-frame $V$-band, extinction-corrected galaxy LF at $z = 3$.

In Paper I the ‘true’ $z \sim 3$ galaxy LF was determined by extinction correcting a modified version of the observationally determined LF of Shapley et al. (2001) of faint-end slope $\alpha = -1.85$. The original Shapley et al. (2001) LF, as well as the extinction-corrected, modified LF, are shown in Fig. 8. Also shown are the corresponding LFs obtained by fitting an LF of faint-end slope $\alpha = -1.57$ (see below) to the Shapley et al. (2001) data. The faint-end slopes of these $z \sim 3$ LFs are steeper than what is found for $z \sim 0$ LFs. Results of semi-analytical galaxy formation models (e.g. Lacey et al. 2005) indicate that this is a natural outcome of hierarchical structure formation scenarios.

Using the extinction-corrected modified Shapley et al. LF in equation (4), and the $m_0(M_V(L_V), \log(T))$ functions determined for the three IMFs as described in the previous section, results in the distributions shown in Fig. 9. For the K98 IMF, the amount of oxygen in the $\log(T) \geq 4.5$ phase is about 1.1 times the amount in the $\log(T) = 4$ ‘cold’ phase. For the S and AY IMFs, the corresponding numbers are about 1.7 and 3.2, respectively. Hence, in particular, for the latter two IMFs, the majority of the gas-phase oxygen is in
Where are the cosmic metals?

Figure 6. Comparison of predicted and actual gas-phase oxygen mass distributions for combinations of various regions simulated using the K98 IMF at high resolution. The top left-hand plot shows the result for the combination of three regions, each containing a galaxy simulated using the 'zoom-in' technique plus a number of companions. The three main galaxies have a mean $M_V$ of $-14.8$. The red solid histogram shows the actual oxygen mass distribution of the three regions combined. The blue dashed histogram shows what the method outlined in the text predicts on the basis of the combined galaxy LF of the three regions. The top right-hand plot shows a similar comparison for a combination of five high-resolution regions containing main galaxies of an average $M_V$ of $-19.5$. The bottom right-hand plot is for the combination of the low- and medium-density 'field' regions described in the text, containing a total of 103 resolved galaxies of $M_V$ down to about $-22.5$. Finally, the bottom left-hand plot shows the results for a higher density 'proto-elliptical' region, containing 60 galaxies of $M_V$ down to about $-22.5$.

In Fig. 9 is also shown the results of adopting a galaxy LF with less steep faint-end slope than the Shapley et al. one. Following Paper I, results are presented for an LF of faint-end slope $\alpha = -1.57$, as found for the rest-frame UV $z \sim 3$ LF by, e.g. (Adelberger & Steidel 2000). Although the results for this LF are qualitatively similar to the ones described above, the amounts of warm and hot phase oxygen decrease somewhat compared to the cold phase ones. The warm/hot to cold/warm gas-phase oxygen mass ratio is $0.8$, $1.1$ and $2.1$ for the K98, Salpeter and AY IMFs, respectively. Moreover, for the AY IMF, the hot to cold/warm gas-phase oxygen mass ratio is unity.

An obvious question is now: for the different gas temperatures, which galaxies contribute mainly to the cosmic gas-phase oxygen budget? In Fig. 10 this is shown using the modified Shapley et al. LF, for the K98 and AY IMFs, respectively. It is seen that for the K98 IMF the main contribution to the log($T$) = 4.5 phase comes from small galaxies, $M_V \sim -16$, and for the AY IMF this is the case for the log($T$) = 5 and 5.5 phases as well (the reason for the large difference between the $M_V$ distributions of log($T$) = 4 and 4.5, say, gas-phase metals is that, whereas the log($T$) = 4 gas is of fairly high density and associated with all galaxies, log($T$) = 4.5 gas is typically diffuse and associated with haloes of comparable virial temperature, i.e. fairly small galaxies).

Given this, and in relation to observational studies, it is clearly of interest to determine how large a fraction of the gas-phase oxygen is associated with galaxies to a certain limiting magnitude. In Fig. 11 this is shown by the long-dashed curves (for the three IMFs of the 'warm'/'hot' rather than cold phase. Moreover, for the AY IMF, the hot to cold/warm gas-phase oxygen mass ratio is 1.1, so the bulk of the oxygen is actually in the hot log($T$) $\gtrsim 5$ phase, rather than in the cold/warm phase. These are some of the main results of this paper.
considered) for the $\alpha = -1.85$ and $-1.57$ LFs. Typical LBG metallicity determinations at $z \sim 3$ only probe to about one magnitude below $L^*$, i.e. $M_V \sim -22$. For the $\alpha = -1.85$ LF, it is found that less than about 20 per cent of the cosmic gas-phase oxygen will be associated with galaxies brighter than this, irrespective of the choice of IMF. For the $\alpha = -1.57$ LF the corresponding fraction is about 30 per cent. Hence, most of the cosmic gas-phase oxygen is associated with galaxies considerably fainter than $L^*$, and is also in this sense ‘missing’.

In calculating the results shown in Fig. 11 it has been assumed that the observational LFs maintain a constant faint-end slope down to $M_V = -10.5$. As can be seen from the figure, in particular for the $\alpha = -1.85$ case this is somewhat critical to the shape of the curves shown. At redshifts $z \sim 3$ the LBG LF is only probed down to a few magnitudes below $L^*$ (but see below). Selecting galaxies using the Ly$\alpha$ line it is possible to probe 2–3 mag fainter still (Fynbo et al. 2001, 2003; Gawiser et al. 2006; Nilsson et al. 2007). This, however, only demonstrates the existence of star-forming galaxies at these redshifts with $M_V \sim -17$ to $-18$, but the data are not good enough to put strong constraints on the shape of the LF. Jakobsson et al. (2005) find that the magnitudes of $z > 2$ gamma-ray burst (GRB) selected galaxies are consistent with being drawn from the steep LF, but the statistics are still poor. We note, however, that Bouwens et al. (2007) were actually able to probe the UV LF at $z \sim 4–6$ down to 4–5 mag below $L^*_{UV}$ and find steep faint-end slopes, $\alpha \sim -1.7$.

Our calculations show, however, that if the slope of the faint-end LF flattens significantly at some brighter $M_V$, then the curves still fairly well represent the result, after appropriate renormalization at this limiting $M_V$ (if the faint-end slope is assumed to be constant to even fainter than $M_V = -10.5$, the results are not much changed compared to the $M_V = -10.5$ results). Moreover, we note that neither the Two-Degree Field Galaxy Redshift Survey (2dFGRS) $b_j$ local LF (Norberg et al. 2002) nor the Sloan Digital Sky Survey

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**Figure 7.** Similar to Fig. 6, but for simulations using the AY IMF. The top left-hand plot shows the result for the combination of three regions, each containing a galaxy simulated using the ‘zoom-in’ technique plus a number of companions. The three main galaxies have a mean $M_V$ of $-14.0$. The top right-hand plot shows results for a combination of two high-resolution regions containing main galaxies of an average $M_V$ of $-16.3$. The bottom right-hand plot is for the combination of the low- and medium-density ‘field’ regions described in the text, containing a total of 40 resolved galaxies of $M_V$ down to about $-21.5$. Finally, the bottom left-hand plot shows the results for a very high-density ‘protocluster’ region, containing 86 galaxies of $M_V$ down to about $-25.5$. The black dotted histogram shows the prediction using a constant $r$ approach (see text); the blue dashed histogram shows the prediction resulting from making the $M_V < -22r$ modification described in the text.
to very similar results to the ones described here. Hence, the results presented are very robust to this.

Secondly, it would be expected that the amount of (in particular) log(T) = 4 cold gas and metal mass available in a simulation at any given time would depend on the star formation efficiency adopted (Section 3). To this end, three K98 galaxy simulations, of galaxies of z = 3 Mv = −19.1, −21.5 and −22.3 and surrounding regions, were run with twice the standard star formation efficiency. Comparing the results of these simulations to the corresponding standard ones, it was found that the total mass of gas-phase oxygen at z = 3 was virtually unchanged, and that the mass of log(T) = 4 oxygen was reduced by ≲5–10 per cent compared to the standard case. Hence, none of the main conclusions about log(T) = 4 metals, obtained in this and the following sections, are affected by such a change. Moreover, a doubling of the star formation efficiency would lead to too small z = 0 disc galaxy gas fractions, and likely also too small disc galaxy angular momenta (SGP03), likely too small z ~ 3 DLA cross-sections (Ellison et al. 2007; Sommer-Larsen et al., in preparation), and SFRs above the Kennicutt (1998) relation.

6 C IV PROPERTIES OF THE LOW- TO INTERMEDIATE-DENSITY IGM

Interesting tests of the abundance and thermal properties of the low-to intermediate-density IGM are provided by QSO absorption-line studies of the Lyman metal forest, as probed by C IV. Songaila (2001) first determined \( \Omega(C IV) \) by integrating the total column density of systems between \( 10^{12} \leq N(C IV) < 10^{13} \text{ cm}^{-2} \) – see also Schaye et al. (2003). As shown by e.g. OD06, this range of column densities trace moderate IGM gas overdensities, \( \delta = \rho_{\text{gas}} / \rho_{\text{gas}}^\text{crit} \sim 1–100 \), or \( n_0 \sim 10^{-2}–10^{-3} \text{ cm}^{-3} \), at \( z \sim 3 \). To obtain a corresponding estimate of \( \Omega(C IV) \) based on our simulations we adopted the following approach.

To convert from total C (as given in our simulations) to C IV abundances, ionization corrections are required. We base our conversion on ionization corrections determined by OD06 using CLOUDY (Ferland et al. 1998). OD06 assumed the Haardt & Madau (2001) UVB in the cosmological simulations, but as shown by Croft et al. (1998), because photo-ionization is subdominant in gas dynamics such a correction yields virtually identical results as having done the simulations with the above (reduced) background. The resulting ionization corrections were kindly supplied to us by Ben Oppenheimer and Romeel Davé, in the form of look-up tables.

In Fig. 12 (left-hand panel) is shown the cumulative \( \Omega(C IV) \) as a function of \( \delta \). For the two simulated ‘field’ galaxy regions the average ratio of the cumulative C IV mass to total (gas-phase) oxygen mass has been determined. This has then been multiplied by \( \Omega_{\text{O}_3, \text{gas}} \), determined on the basis of the results obtained in the previous section. As is clear from this section, the value of \( \Omega_{\text{O}_3, \text{gas}} \) depends on the actual form of galaxy LF. To obtain lower and upper limits on \( \Omega_{\text{O}_3, \text{gas}} \), we evaluate it at \( M_v = -21 \) and -10, respectively, assuming the \( \alpha = -1.85 \) LF. \( M_v = -21 \) corresponds approximately to the detection limit of Shapley et al. (2001), whereas \( M_v = -10 \) corresponds to assuming that the faint-end slope remains constant to this very faint magnitude. As can be seen from Fig. 11, using the \( \alpha = -1.57 \) LF provides less conservative limits. In the figure is shown the result of applying the lower and upper limits for the K98, Salpeter and AY IMFs, respectively. Using other simulated regions, centred on smaller galaxies, yields similar results. Using
Figure 10. Contribution to cosmologically averaged gas-phase oxygen density as a function of galaxy V-band absolute magnitude for the K98 (left-hand panel) and AY (right-hand panel) IMFs. Curves corresponding to different gas temperatures are colour coded as in Fig. 2 [log(T) = 4: green, 4.5: blue, 5: cyan, 5.5: magenta, 6: black, 6.5: red]. The results shown are for the extinction-corrected modified Shapley et al. (α = −1.85) galaxy LF. For comparison with the cosmological density parameter, see caption of Fig. 9.

Figure 11. Fractional contribution to the cosmologically averaged gas-phase oxygen density by galaxies brighter than $M_V$, for the extinction-corrected modified Shapley et al. LF (left-hand panel) and the LF of faint-end slope $-1.57$ (right-hand panel). Green, blue and red curves correspond to results for the K98, Salpeter and AY IMFs, respectively. Long-dashed curves correspond to gas-phase oxygen, short-dashed curves to stellar oxygen and solid curves to the total.

As can be seen, the chemical yield of the K98 IMF appears too low to match the observational estimates, whereas the Salpeter and AY IMFs can match the observations, and an IMF with a yield in between these two appears optimal. We caution, however, that our estimates of $\Omega_{\text{C IV}}$ depend on the adopted gas-phase oxygen to C IV mass conversions. The optimal would be to carry out simulations of $\geq 100 \, h^{-1} \, \text{Mpc}$ box size cosmological volumes at the (high) resolution of our galaxy formation runs, but as mentioned previously, this is currently computationally prohibitive. Hence, our result above on the cosmic IMF should be seen as indicative only.

The main point is that both the Salpeter and AY IMF simulations can match the observational constraints on $\Omega_{\text{C IV}}$.

Observations of C IV linewidths for the above column density range can be used to probe the thermal properties of the low-density IGM. Three components contribute to the linewidths: (i) thermal broadening, (ii) spatial broadening due to Hubble expansion across the physical extent of the absorber and (iii) turbulent broadening. The last component can be ignored, since the IGM at these overdensities is very quiescent (Rauch et al. 2005). Observational estimates of C IV linewidths by Boksenberg et al. (2003) indicate $b \simeq 10 \, \text{km s}^{-1}$ in the range $z \sim 1.5$–4.5 for $10^{13} \lesssim N(\text{C IV}) < 10^{15}$.
10^{14} \text{ cm}^{-2} \) absorbers. This can be used to derive upper limits to the \( \text{C IV} \) abundance-weighted IGM temperature. As the thermal component of the \( \text{C IV} \) linewidth is given by \( b_{\text{th}} = 3.7 \sqrt{T/10^4} \), \( \text{C IV} \) abundance-weighted IGM temperatures of less than \( \sim 5 \times 10^5 \text{ K} \) are indicated. In Fig. 12 (right-hand panel) we show \( \text{C IV} \) abundance-weighted IGM temperatures a function of \( \delta \) in the ‘field’ galaxy regions for the three IMFs considered (results for other regions are quite similar). It is seen that models in general satisfy the above IGM temperature criterion. Moreover, our predictions of the abundance-weighted IGM temperatures agree well with the predictions of OD06 for their best fitting ‘momentum-driven’ wind model.

Finally we note that in the future it will be possible to probe the metal enrichment of the IGM to even lower densities using \( \text{O VI} \) – see e.g. Schaye et al. (2000).

7 Combining the Cosmic Stellar and Gas-Phase Oxygen Distributions

With the results on the cumulative cosmic gas-phase oxygen distributions presented in the previous section and the results on the similar distributions for the stellar oxygen from Paper I, we can now assess the relative importance of the two components. In Fig. 11 results for the normalized gas-phase oxygen distributions are shown by long-dashed curves, the stellar distributions are shown by the short-dashed curves, and the combined distributions by the solid curves (for the three IMFs considered) for the \( \alpha = -1.85 \) and \(-1.57 \) LFs [we note that stellar oxygen refers to oxygen in galactic stars only, but since the amount of oxygen in intergalactic stars is, in comparison, very small (Paper I), we neglect this component in the following].

As can be seen, the combined distributions are for all three IMFs dominated by the gas-phase oxygen, and increasingly so going from the K98 to the AY IMF. For the \( \alpha = -1.85 \) LF, it is found that less than about 25 per cent of the total cosmic oxygen is associated with galaxies brighter than \( M_V = -22 \), irrespective of the choice of IMF. For the \( \alpha = -1.57 \) LF the corresponding fraction is about 35 per cent for the AY IMF, and about 40 per cent for the K98 and Salpeter IMFs.

Fig. 13 shows, for the \( \alpha = -1.85 \) LF, and the three IMFs, the cumulative partition between gas-phase oxygen and stellar oxygen as a function of \( M_V \). It is seen, that if the faint-end slope of \(-1.85 \) holds down to \( M_V \sim -12 \), then the cumulative gas-phase oxygen fractions are 72, 79 and 92 per cent for the K98, Salpeter and AY IMFs, respectively, so, as stated above, for all three IMFs, the amount gas-phase oxygen dominates over the amount stellar oxygen. For the \( \alpha = -1.57 \) LF these fractions drop slightly to 64, 71 and 88 per cent.

As discussed in Section 5 the calculations assume a constant faint-end slope down to \( M_V = -10.5 \). If the LF is assumed to display a significant flattening at a brighter magnitude than this, then the figure can still be used to determine the gas-phase/stellar oxygen partition to such a limiting \( M_V \). Assuming, for example, that the faint-end slope is constant to at least 6 mag below \( M^* \) (i.e. \( M_V \sim -17 \)), which is the case for local LFs (Section 5), results in lower limits on the cumulative gas-phase oxygen fractions of 65, 72 and 90 per cent for the \( \alpha = -1.85 \) LF, i.e. not much different from the results quoted above.

We can now finally compare the integral constraints on the average cosmic oxygen density at \( z = 3 \), obtained in Section 2, to what is obtained by combining detailed high-resolution galaxy formation simulations with the observed (corrected) \( z \sim 3 \), V-band LF. In Fig. 14 we show the cumulative oxygen density versus \( M_V \) for the three IMFs and the two faint-end LF slopes considered. Also shown are the constraints from the ‘minimum’, ‘median’ and ‘maximum’ oxygen production rate density models discussed in Section 2. In order to enable a meaningful comparison, the latter results should be compared to the former evaluated at certain limiting magnitudes. These magnitudes should be chosen to be brighter than or equal to about \( M_V \simeq -21.0, -20.5 \) and \(-20.0 \) for the K98, Salpeter and AY IMFs, respectively, for the following reasons.

Kennicutt (1998) finds a relation between UV luminosity and SFR, namely

\[
\text{SFR} (\text{M}_\odot\text{ yr}^{-1}) = 1.4 \times 10^{-28} \beta_{\text{IMF}} L_V (\text{erg s}^{-1} \text{ Hz}^{-1}),
\]

with \( \beta_{\text{IMF}} = 1.0 \) for the Salpeter IMF. Given that the yield of the Kroupa (1998) IMF is smaller than for the Salpeter IMF, and vice versa for the AY IMF, \( \beta_{\text{IMF}} \) will be larger and smaller than unity for

Figure 12. Cumulative cosmic \( \text{C IV} \) density, in units of the critical, \( \Omega(\text{C IV}) \) as a function of the gas overdensity \( \delta = \rho_{\text{gas}}/\rho_{\text{crit}} \) (left-hand panel). Green, blue and red curves correspond to the K98, Salpeter and AY IMFs. Solid curves correspond to upper limits, dashed curves to lower limits. Also shown, as a horizontal, black solid line, is the median of 10 observational estimates at redshifts in the range 1.5–4.5 taken from Songaila (2001), Boksenberg et al. (2003) and Songaila (2005). Horizontal black dashed lines show 1σ deviations, where \( \sigma \) is the variance of the observational estimates. The plot to the right-hand side shows the median \( \text{C IV} \) abundance-weighted temperature of the IGM as a function of gas overdensity, for the three IMFs.

Figure 13 shows, for the \( \alpha = -1.85 \) LF, and the three IMFs, the cumulative partition between gas-phase oxygen and stellar oxygen as a function of \( M_V \). It is seen, that if the faint-end slope of \(-1.85 \) holds down to \( M_V \sim -12 \), then the cumulative gas-phase oxygen fractions are 72, 79 and 92 per cent for the K98, Salpeter and AY IMFs, respectively, so, as stated above, for all three IMFs, the amount gas-phase oxygen dominates over the amount stellar oxygen. For the \( \alpha = -1.57 \) LF these fractions drop slightly to 64, 71 and 88 per cent.

As discussed in Section 5 the calculations assume a constant faint-end slope down to \( M_V = -10.5 \). If the LF is assumed to display a significant flattening at a brighter magnitude than this, then the figure can still be used to determine the gas-phase/stellar oxygen partition to such a limiting \( M_V \). Assuming, for example, that the faint-end slope is constant to at least 6 mag below \( M^* \) (i.e. \( M_V \sim -17 \)), which is the case for local LFs (Section 5), results in lower limits on the cumulative gas-phase oxygen fractions of 65, 72 and 90 per cent for the \( \alpha = -1.85 \) LF, i.e. not much different from the results quoted above.

We can now finally compare the integral constraints on the average cosmic oxygen density at \( z = 3 \), obtained in Section 2, to what is obtained by combining detailed high-resolution galaxy formation simulations with the observed (corrected) \( z \sim 3 \), V-band LF. In Fig. 14 we show the cumulative oxygen density versus \( M_V \) for the three IMFs and the two faint-end LF slopes considered. Also shown are the constraints from the ‘minimum’, ‘median’ and ‘maximum’ oxygen production rate density models discussed in Section 2. In order to enable a meaningful comparison, the latter results should be compared to the former evaluated at certain limiting magnitudes. These magnitudes should be chosen to be brighter than or equal to about \( M_V \simeq -21.0, -20.5 \) and \(-20.0 \) for the K98, Salpeter and AY IMFs, respectively, for the following reasons.

Kennicutt (1998) finds a relation between UV luminosity and SFR, namely

\[
\text{SFR} (\text{M}_\odot\text{ yr}^{-1}) = 1.4 \times 10^{-28} \beta_{\text{IMF}} L_V (\text{erg s}^{-1} \text{ Hz}^{-1}),
\]

with \( \beta_{\text{IMF}} = 1.0 \) for the Salpeter IMF. Given that the yield of the Kroupa (1998) IMF is smaller than for the Salpeter IMF, and vice versa for the AY IMF, \( \beta_{\text{IMF}} \) will be larger and smaller than unity for
these two IMFs, respectively. Quantitatively we find that $\beta_{\text{ISM}} \simeq 1.7$ and 0.4 for the K98 and AY IMFs, respectively. The absolute UV magnitude ($\lambda \sim 1500$ Å) characterizing the observed galaxy LF at $z \sim 3$ (i.e. corresponding to $L_{\text{UV},z=3}$) is $M_{\text{UV},z=3} \simeq -21.0$ (e.g. Steidel et al. 1999, after correction to the adopted cosmology, Sawicki & Thompson 2006). Following Sawicki & Thompson (2006), and using equation (5) above, one can show that this absolute magnitude corresponds to a (unextinguished) SFR of about $15\beta_{\text{ISM}}$ $M_\odot$ yr$^{-1}$. With a dust correction of about a factor of 5.5 at $z \sim 3$ (Section 2) the above observed $M_{\text{UV},z=3}$ hence corresponds to a true (un-obscured) SFR of about 82 $\beta_{\text{ISM}}$ $M_\odot$ yr$^{-1}$. We shall now consider two models for the $\lambda \sim 1500$ Å extinction as a function of redshift for $z \geq 3$. Model A assumes a constant extinction factor of 5.5 at all $z \geq 3$ (cf. Section 2), whereas model B is a low-extinction model assuming factors of 4.2, 3, 2 and 1.5 at $z = 3, 4, 5$ and 6, respectively (cf. Bouwens et al. 2006). For model A, a galaxy of observed $L_{\text{UV}} = 0.1 \times L_{\text{UV},z=3}$ will have SFRs of about 6.3, 4.5, 3.0 and 2.3 $M_\odot$ yr$^{-1}$ at $z = 3, 4, 5$ and 6, respectively. We find that only galaxies of (unextinguished) $M_{\text{V}}$ at $z = 3$ brighter than about $-22.0, -21.5$ and $-20.5$ for the K98, Salpeter and AY IMFs, respectively. For model B, the above $M_{\text{UV},z=3}$ corresponds to a true SFR of about 63 $\beta_{\text{ISM}}$ $M_\odot$ yr$^{-1}$, and galaxies of observed $L_{\text{UV}} = 0.1 \times L_{\text{UV},z=3}$ will have SFRs of about 6.3, 4.5, 3.0 and 2.3 $M_\odot$ yr$^{-1}$ at $z = 3, 4, 5$ and 6, respectively. We find that only galaxies of (unextinguished) $M_{\text{V}}$ at $z = 3$ brighter than about $-21.5, -21.0$ and $-20.5$ for the above three IMFs, respectively, will satisfy this. Moreover, even assuming (very conservatively) zero extinction at $z \gg 6$, corresponding to a ‘limiting’ (unextinguished) SFR of about 1.5 $M_\odot$ yr$^{-1}$, all galaxies of such $z \geq 6$ SFRs will be brighter than about $M_{\text{V}} = -21.5, -21.0$ and $-20.5$ at $z = 3$ for the three IMFs, respectively. Assuming lower luminosity limits of $M_{\text{V}} = -21.0, -20.5$ and $-20.0$ for the three IMFs is hence very conservative – these limits are indicated in Fig. 14 by vertical dashed lines.

From Fig. 14 it follows that galaxy models based on the K98 IMF cannot meet the constraint set by the observed UV luminosity density history – the oxygen (and general metal) yield of this IMF is simply not sufficiently large. The same is the case for the Salpeter IMF.
than about 1/4 of the cosmic oxygen is associated with LBGs sufficiently bright, \( M_V \gtrsim -22 \), for direct abundance determination, using oxygen lines emitted from \( \text{H} \text{ii} \) regions around young stars in the galaxies (e.g. Pettini et al. 2001). For the \( \alpha = -1.57 \) LF this fraction increases slightly, to about 35 per cent. Furthermore, in Section 7 it was shown that for both LFs the major part of the cosmic oxygen is in the gas-phase, rather than in stars. In particular, for the Salpeter and AY IMFs, which emerge from the previous section as the more plausible, the gas-phase oxygen fraction exceeds 70 per cent.

FSB05 found a factor of about 5 discrepancy between the amount of metal in the stars of LBGs and what is predicted from the integrated UV luminosity density history. They assumed typical LBG stellar masses of \( 2 \times 10^{10} \, \text{M}_\odot \), corresponding to \( M_V \sim -22.5 \), i.e. close to \( M_V > -3 \).

In Fig. 13 is shown, for the \( \alpha = -1.85 \) LF, the cumulative stellar cosmic oxygen density. For the K98 IMF, the ratio between the stellar oxygen density to \( M_V \sim -21 \) and what is obtained from the median model (Section 7) is 0.10. For the Salpeter and AY IMFs, evaluated at \( M_V = -20.5 \) and \(-20 \), the corresponding ratios are 0.17 and 0.20. For the \( \alpha = -1.57 \) LF the corresponding ratios are 0.14, 0.24 and 0.29, for the K98, Salpeter and AY IMFs, respectively. Given that the AY models overpredict the metallicities of LBGs of \( M_V \sim -22 \) to \(-23 \) by about 0.2 dex relative to observations (Paper I), the above ratios for the AY models should be reduced to 0.13 and 0.18 for the \( \alpha = -1.85 \) and \(-1.57 \) LFs, respectively.

The above results are obtained, however, by including stellar oxygen mass all the way down to \( M_V \sim -20.5 \). If one only includes stellar oxygen mass to \( M_V \sim -22.5 \), all the above fractions are reduced by about a factor of 2. Hence the discrepancy discussed above, denoted by FSB05 and others as ‘the missing metals problem’, is actually about twice larger than originally found by FSB05.

DO07 predicted that at \( z \sim 3 \), about 50 per cent of the gas-phase metals should reside in the diffuse IGM (gas outside the virial radii of galaxy haloes, and of \( T < 3 \times 10^4 \) K). We cannot compare the results found in the previous sections directly to theirs, since different gas-phase criteria have been used. However, our \( \log(T) = 4.5 \) gas criterion is similar to theirs for diffuse IGM, though we also include \( \log(T) = 4.5 \) metals inside of galaxy virial radii in our estimate (see also below; note also that we find almost all the \( \log(T) = 4 \) phase metals to reside in gas of fairly high density, \( n_H \gtrsim 0.1 \text{ cm}^{-3} \), so there is essentially no overlap between this phase and DO07’s diffuse phase).

For the \( \alpha = -1.85 \) LF we find \( \log(T) = 4.5 \) to total gas-phase metal fractions of 34, 31 and 26 per cent for the K98, Salpeter and AY IMFs, respectively. For the \( \alpha = -1.57 \) LF, the corresponding fractions are 21, 20 and 18 per cent. If we try to mimic the criterion of DO07 better, by selecting all metals in gas of \( T < 3 \times 10^4 \) K and \( \delta = \rho_{\text{gas}}/\rho_{\text{gas}} \lesssim 100 \), then for the field galaxy regions we find ‘diffuse IGM’ oxygen fractions of 4, 4 and 6 per cent for the K98, Salpeter and AY IMFs, respectively. If we use the protocluster regions, which are the only simulations at our disposal with a resolution comparable to the (fairly modest) numerical resolution of DO07’s 32 \( h^{-1} \text{Mpc} \) box size simulation, the corresponding fractions drop to \sim 1 per cent for all IMFs. However, we stress that the temperature of the protocluster IGM is larger than that of the average IGM, but in any case significantly lower ‘diffuse IGM’ metal fractions, than predicted by DO07, are indicated.

DO07 used the Springel & Hernquist (2003) ‘subgrid’ approach to model star formation. They predict that about 20 per cent of the gas-phase metals reside in star-forming gas. In our models, which invoke explicit two-phase modelling of the ISM, gas of \( T \sim 10^4 \) K and \( n_H \gtrsim 0.1 \text{ cm}^{-3} \) is potentially star forming. Hence we compare our results for the \( \log(T) = 4 \) gas-phase metal content to the above

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**Figure 14.** Contribution to the cosmologically averaged total (gas-phase and stellar) oxygen density by galaxies brighter than \( M_V \), for the modified Shapley et al. LF, and the LF of faint-end slope \(-1.57 \). Green, blue and red curves correspond to results for the K98, Salpeter and AY IMFs, respectively (for comparison with the cosmological density parameter, see caption of Fig. 9). In the right-hand side of the plot, the \( \alpha = -1.57 \) curves are above the corresponding \( \alpha = -1.85 \) ones. Also shown, by horizontal dashed lines, are the constraints from the integrated cosmic oxygen production history derived in Section 2. Finally, the lower \( V \)-band luminosity limits, at which the predictions for the various IMFs and LFs should be compared to the integral constraints, are shown by green, blue and red vertical dashed lines for the K98, Salpeter and AY IMFs, respectively – see text for details.

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**8 MISSING METALS AND COMPARISON TO OTHER WORKS**

In Section 5 it was shown that for the \( \alpha = -1.85 \) and \( 3 \) LF, less than about 1/4 of the cosmic oxygen is associated with LBGs sufficiently bright, \( M_V \gtrsim -22 \), for direct abundance determination,
of DO07 [as noted above, almost all log(T) = 4 metals reside in gas of \( n_H \gtrsim 0.1 \text{ cm}^{-3} \)]. For the \( \alpha = -1.85 \) LF we find log(T) = 4 to total gas-phase metal fractions of 47, 37 and 26 per cent for the K98, Salpeter and AY IMFs, respectively. For the \( \alpha = -1.57 \) LF, the corresponding fractions are 57, 47 and 32 per cent. Hence we find somewhat larger metal fractions in star-forming gas, than do DO07. A more important difference is, however, that DO07 at \( z \sim 3 \) find no metal containing gas at densities \( n_H \gtrsim 0.01 \text{ cm}^{-3} \). This result is strongly at variance with our results, and it would seem difficult for such models to match the large amount of DLA cross-section observationally detected at such redshifts, although further analysis obviously is required to clarify this.

Finally, we can compare the \( z = 3 \) gas-phase metal temperature distribution predicted by DO07 to our results. Qualitatively, our predictions for the K98 and Salpeter IMFs agree with that of DO07, in yielding temperature distributions, which peak at \( T \sim 10^4 \) K and decrease towards larger temperatures. However, for the AY IMF the results are very different. Moreover, quantitatively our results for the K98 and Salpeter IMFs disagree significantly with those of DO07 at the ‘high-T’ end: DO07 find that \( \lesssim 5 \) per cent of the gas-phase metals reside in gas of \( T > 10^{7.5} \) K. In comparison, we find for the \( \alpha = -1.85 \) LF that the corresponding fractions are 20, 32 and 51 per cent for the K98, Salpeter and AY IMFs, respectively, and for the \( \alpha = -1.57 \) LF, 21, 32 and 50 per cent. Hence for any of the IMFs considered, we predict significantly larger fractions of ‘high-T’ gas-phase metals than do DO07.

8.1 Metals in the cold gas-phase and DLA absorbers

The log(T) = 4 phase is found to be the most prominent metal containing gas-phase for the K98 and Salpeter IMFs, and also to be quite prominent for the AY IMF. As the metals in this phase typically reside in gas of densities \( n_H \gtrsim 0.1 \text{ cm}^{-3} \), one would expect a significant fraction of these metals to be situated at column densities typical of DLAs, namely \( N(H) \gtrsim 10^{20.3} \text{ cm}^{-2} \). However, in general DLAs have very low abundances – significantly less than Galactic stars with similar ages (Pettini et al. 1990; Pettini 1999; Lu et al. 1996; Kulkarni & Fall 2002; Prochaska et al. 2003; Akerman et al. 2005; Zwaan et al. 2005; Ermi et al. 2006). Expressed in terms of the global metal content of the LBG stars, we predict similar to three times as large amounts of metals in the log(T) = 4 phase (depending on the IMF), whereas observations of DLAs only indicate a fraction of about 10–20 per cent (e.g. FSBO5; Prochaska et al. 2006). It is obviously of importance to understand the reason for this apparent discrepancy. Although we will defer a thorough discussion of DLAs to a forthcoming paper (Sommer-Larsen et al., in preparation), we briefly address the above issue in the following.

Ellison et al. (2007) analysed two of the very high-resolution simulations, described in the following section, in relation to DLA properties. The two simulations represent the formation and evolution of two disc galaxies, of \( z = 0 \) characteristic circular velocities \( V_c = 245 \text{ and } 180 \text{ km s}^{-1} \). The galaxies were selected from a larger sample to represent two different disc formation evolutionary paths: for the \( V_c = 180 \text{ km s}^{-1} \) galaxy the disc starts growing steadily already by \( z \sim 2.5 \), whereas for the other galaxy disc growth is merger induced, and the disc grows strongly from \( z \sim 1 \) to 0 (see also Robertson et al. 2004). Ellison et al. determined the DLAs/sub-DLA characteristics of these two protogalaxies at \( z = 3.6, 3.0 \) and 2.3, with focus on determining neutral column density distributions, and the probability of detecting coincident 100-kpc scale DLAsub-DLA absorption in individual galaxies at such redshifts – we refer the reader to Ellison et al. for more detail, as well as images of the objects.

Here we build on the analysis by Ellison et al. of these two (proto)galaxies. In Fig. 15 (left-hand panel) we show the normalized cumulative oxygen mass in the absorber above log(N(HI)) = 20.3 versus the cumulative absorber area, starting at the highest H I surface densities, log(N(HI)) ~ 24. and going down to log(N(HI)) = 20.3. For each galaxy results for ‘face-on’ and one ‘edge-on’ projections are shown. As can be seen, about 90 per cent of the total oxygen mass of the absorber resides in 1 per cent of the total absorber area for both projections. From Fig. 15 (centre) it is moreover seen that this oxygen mass is associated with column densities log(N(HI)) \gtrsim 22.5. DLAs of such high column densities have never been detected in QSO spectra, which of course is not surprising given the above findings. Moreover, at such high densities, formation of molecular hydrogen is likely to take place (Schaye 2001b; Zwaan & Prochaska 2006). Although the process of H2 formation is not included in the hydro/gravity simulations, it is clear that the properties of the high-density gas can be significantly affected by H2 formation (e.g. Pelupessy, Papadopoulos & van der Wer 2006). Greve & Sommer-Larsen (2007) showed that the effects of H2 formation can be approximately determined post-process on the basis of the cosmological galaxy formation simulations – this will be one of the main topics of a forthcoming paper on DLAs (Sommer-Larsen et al., in preparation). H2 molecules have been detected in DLAs, but only at relatively low fractions of less than a tenth relative to atomic hydrogen (Ledoux et al. 2003). Moreover, H2 is preferentially detected in the highest metallicity DLAs (Petitjean et al. 2006). At
this point it is sufficient to note that (i) only a very small fraction of QSO sightlines will probe the high-metallicity regions of DLAs and (ii) due to H₂ formation these regions may possibly be difficult to probe in neutral hydrogen (Zwaan & Prochaska 2006). We also note from Fig. 15 (right-hand panel) that the metal abundances of the high column density regions are significantly larger than what is typically observed in DLAs, whereas at log(N(HI)) ≲ 22 they are not (e.g. Pettini et al. 2003). Finally, we note that the high column density regions will likely be characterized by significant dust contents, which could further bias against selecting QSO sightlines passing through such regions. Evidence for dust in DLAs has been reported (Pei, Fall & Bechtold 1991; Vladilo et al. 2006). This may naturally explain why DLA column densities of log(N(HI)) ≳ 22 are very rare (Vladilo & Péroux 2005; Vladilo et al. 2006). However, studies of radio selected DLAs (free from dust-bias) have found similar column density and metallicity distributions to optically selected DLA samples (Ellison et al. 2001, 2004; Ellison, Hall & Lira 2005; Akerman et al. 2005; Jorgenson et al. 2006). Also, Murphy & Liske (2004) find no excess absorption towards QSOs with DLAs (but this study is based on an optically selected DLA sample). It remains to be clarified to which extent dust bias is important for DLA column density and metallicity studies, especially at log(N(HI)) ≳ 22. In particular, a larger sample of radio selected DLAs is needed (Jorgenson et al. 2006, Ellison et al. 2007, private communication).

We note that DLAs at z ≈ 2 with near solar metallicity have been found (Ledoux et al. 2002). Also, the SDSS has been used to strongly increase the sample of DLAs (Prochaska, Herbert-Fort & Wolfe 2005) and among these 5 per cent have very strong metal-line absorption (Herbert-Fort et al. 2006). Some of these 5 per cent are metal-rich DLAs, although some could be relatively metal-poor DLAs with very high hydrogen column densities. About 60 per cent of the metal-strong DLAs have detected molecular hydrogen (Militinovic et al., in preparation).

Interestingly, DLAs with log(N(HI)) ≳ 22 have been detected in the spectra of the optical afterglows of GRBs (Jakobsson et al. 2006; Watson et al. 2006; Prochaska et al. 2007). The selection function for GRB sightlines is completely different than the cross-section selection of QSO DLAs. GRB sightlines are strongly correlated with the blue light of their host galaxies (Bloom, Kulkarni & Djorgovski 2002; Fruchter et al. 2006) most likely tracing the location of the most massive stars (M ≳ 20M⊙, Larsson et al. 2007). Significant dust obscuration is observed for at least some of the log(N(HI)) ≳ 22 GRB DLAs (Watson et al. 2006). Furthermore, it has been found that the metallicities inferred for DLAs in GRB hosts are systematically higher than for QSO DLAs and that GRBs hence may offer a new probe of early cosmic chemical evolution complementary to the QSO DLAs and LBGs (Fynbo et al. 2006; Savaglio 2006; Prochaska et al. 2007).

In conclusion, the low metallicities inferred from QSO DLAs do not exclude that significant amounts of metals can reside in the log(T) = 4 phase. The reason for this is most likely that the total cross-section for this component is only of the order of a few per cent of the total DLA cross-section (see also Johansson & Efstathiou 2006) and that the current DLA samples are too small to uncover them (see also Zwaan & Prochaska 2006), but dust bias, as well as H₂ formation, will probably also be of importance.

9 NUMERICAL RESOLUTION

In SGP03 and Sommer-Larsen (2006) it has been shown that the results of cosmological galaxy formation and evolution using our code are, in general, robust to changes of the numerical resolution. However, in this paper we present gas-phase metal temperature distributions and other results, which have not been presented before. It is hence clearly important to demonstrate that these results are resolution robust as well. To this end we carried out three very high-resolution K98 IMF simulations, of eight times higher mass and two times higher force resolution compared to ‘standard’. We simulated three (proto)disc galaxies, which at z = 0 have characteristic circular velocities of 245, 180 and 66 km s⁻¹, respectively. The oxygen masses for the smaller galaxy have been multiplied by a factor 50 for clarity. The slight offset between the results for the smaller galaxy is due to high-resolution protogalactic region being slightly smaller than the corresponding normal resolution one.

Due to computational limitations we did not perform similar resolution tests for the two other IMFs considered, but we have no reason to believe that simulations based on these IMFs would perform less well in resolution tests. We conclude that the results obtained in this paper are robust to resolution changes.

Figure 16. Gas-phase oxygen temperature distributions for three protogalactic regions simulated at both very high (blue dashed histograms) and normal (red solid histograms) numerical resolution. The three protogalaxies become at z = 0 disc galaxies of characteristic circular velocities V_c = 245, 180 and 66 km s⁻¹, respectively. The oxygen masses for the smaller galaxy have been multiplied by a factor 50 for clarity. The slight offset between the results for the smaller galaxy is due to high-resolution protogalactic region being slightly smaller than the corresponding normal resolution one.
10 SUMMARY AND CONCLUSIONS

The global temperature distribution of the cosmic gas-phase oxygen at $z \sim 3$ has been determined by combining high-resolution cosmological simulations of individual protogalactic, as well as larger, regions with extinction-corrected, observationally based, V-band (rest-frame) galaxy LFs of faint-end slopes $\alpha = -1.85$ and $-1.57$. The simulations have been performed with three different stellar IMFs, a Kroupa (K98), a Salpeter (S) and an AY, spanning a range of a factor of 5 in chemical yield and specific SNII energy feedback. Gas-phase oxygen is binned according to $T\sim 4.0$ (‘cold’), $4.5$ (‘warm’), and $5.0$, $5.5$, $6.0$, $6.5$, $7.0$ (‘hot’ phases). Below we summarize results for the $\alpha = -1.85$ LF, but results for the $\alpha = -1.57$ LF are similar.

Oxygen is found to be distributed over all $T$ phases, in particular for the (‘top-heavy’) AY IMF. But, at variance with previous works, it is found that, for the K98 and Salpeter IMFs, the most important phase is the cold one, which contains 47 and 37 per cent of all gas-phase oxygen, mainly in gas at fairly high density, $n_\text{H} > 0.1 \text{ cm}^{-3}$, and potentially star forming. Moreover, the cold phase alone contains 1.3, 1.5 and 3.2 times the mass of oxygen in galactic stars for the three IMFs. The implications of this in relation to observational DLA studies are discussed on the basis of very-high-resolution simulations of two (proto)disc galaxies, with emphasis on oxygen and iron abundances. It is concluded, that the reason why current DLA surveys only detect a cold ISM metal fraction of about 20 per cent relative to the metal mass in galactic stars is that the total cross-section for the high-metallicity component is only of the order of a few per cent of the total DLA cross-section, and that the current DLA samples are too small to uncover it. Moreover, in addition, dust bias, as well as $H_2$ formation, will likely also be of importance.

In relation to ‘missing metals’ it is found that the ratio of gas-phase to stellar oxygen mass is 2.7, 3.9 and 13, and the ratio of warm + hot to cold gas-phase oxygen mass is 1.1, 1.7 and 3.2 for the three IMFs. For the AY IMF, the hot phases actually contain more oxygen than the cold + warm.

In conclusion, a significant fraction of the cosmic oxygen may be difficult or impossible to detect. In addition, it is found that less than about 20–30 per cent of the cosmic oxygen will be associated with galaxies brighter than $M_V \sim -22$, i.e. the faintest galaxy luminosities probed by current LBG metallicity determinations (about 1 mag below $L^*$. Hence, 70–80 per cent of the cosmic oxygen is also in this sense ‘missing’.

From the LBG-based, $\lambda \sim 1500 \text{ Å}$ UV luminosity density history at $z \geq 3$, we obtain an essentially IMF-independent constraint on the mean cosmic oxygen density at $z = 3$. We compare this to what is obtained from our models, for the three different IMFs. We find that the (solar neighbourhood type) K98 IMF is strongly excluded, as the chemical yield is simply too small, the Salpeter is marginally excluded, and the AY matches the constraint well. The optimal IMF would have a yield intermediate between the S and AY. The K98 IMF can only match the data if the $\lambda \sim 1500 \text{ Å}$ extinction corrections have been overestimated by factor of $\sim 4$, which seems highly unlikely, cf. Reddy & Steidel (2004).

Using carbon abundances, and C to C IV ionization corrections, we estimate $\Omega(C\IV)\text{ at moderate IGM gas overdensities, } \delta = \rho_\text{gas}/\rho_\text{crit} \sim 1-100$ for the three IMFs, and compare to observational results. As above, we find that the yield of the K98 IMF is too small to match the data, whereas models based on the Salpeter and AY IMFs can match the data, with the optimal IMF in between the two. Moreover, we show that for all IMFs, C IV abundance-weighted IGM temperatures are moderate, $T \lesssim 4 \times 10^4 \text{ K}$, consistent with observational constraints on C IV linewidths.

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