On the enrichment of the intergalactic medium by galactic winds

Biman B. Nath\textsuperscript{1*} and Neil Trentham\textsuperscript{2}

\textsuperscript{1}Inter-University Centre for Astronomy and Astrophysics, Post Box 4, Ganeshkhind, Pune – 411007, India
\textsuperscript{2}Institute for Astronomy, 2680 Woodlawn Drive, University of Hawaii, Honolulu, HI 96822, USA

Accepted for publication in the MNRAS

ABSTRACT
Observations of metal lines in Lyα absorption systems of small H I column density and their ubiquitous nature suggest that the intergalactic medium (IGM) was enriched to about $Z \sim 0.01 Z_\odot$ by a redshift $z \sim 3$. We investigate the role of winds from small star-forming galaxies at high $z$ in enriching the IGM. The existence of large numbers of small galaxies at high $z$ follows naturally from hierarchical clustering theories (e.g. CDM).

For analytical simplicity we assume that the galactic winds escape the galaxies at a single characteristic redshift $z_{in}$, and we model the galactic winds as spherical shock waves propagating through the IGM. We then calculate the probability distribution of the metallicity of the IGM, as a function of time (for different values of $z_{in}$), adopting plausible galaxy mass functions (from Press-Schechter formalism), cooling physics, star-formation efficiencies, gas ejection dynamics, and nucleosynthesis yields.

We compare this expected distribution with the observed distribution of metallicities in the Lyα forest at $z = 3$, the metal poor stars in the halo of our Galaxy, and with other observational constraints on such a scenario. We find that galactic winds at high $z$ could have enriched the IGM to a mean metallicity of $Z \sim 0.01 Z_\odot$ at $z \sim 3$, with a standard deviation of the same order, if $z_{in} \sim 5$, and that this satisfies all the observational constraints.

Key words: cosmology : early Universe – galaxies : formation – galaxies : abundances – galaxies : evolution – galaxies : intergalactic medium – galaxies : quasars : absorption lines – stars: Galactic halo – stars: abundances – stars: supernovae

1 INTRODUCTION
Recent observations with the Keck 10 m telescope have shown that relatively low H I column density Lyα absorption lines ($N_{HI} \lesssim 10^{14} \text{ cm}^{-2}$) at $z \sim 3$ have corresponding metal lines. Cowie et al. (1995), Tytler et al. (1995) and Womble et al. (1996) reported that more than half of all Lyα absorption systems with $N_{HI} \gtrsim 10^{14} \text{ cm}^{-2}$ have CIV. These observations confirmed previous suggestions of enrichment in the Lyα forest clouds (Meyer & York 1987; Tytler 1987).

More recently, Songaila & Cowie (1996) have detected lines due to several other ions such as SIV. They have also claimed that the fraction of Lyα lines with associated metal lines is larger than $\sim 0.5$ as reported earlier. They found C IV lines in 90% of clouds with $N_{HI} > 1.6 \times 10^{15} \text{ cm}^{-2}$ and 75% of clouds with $N_{HI} > 3.0 \times 10^{14} \text{ cm}^{-2}$. They emphasize that it would be difficult to estimate the exact fraction of Lyα lines with associated metal lines with $N_{HI} \lesssim 10^{15} \text{ cm}^{-2}$ as it would mean detecting C IV lines with $N_{C IV} \gtrsim 10^{11} \text{ cm}^{-2}$ which is difficult at present. It is also of interest that Songaila & Cowie (1996) found evidence of enhancement of the alpha process elements versus the Fe process elements, as is also the case in damped Lyα systems (Lu et al. 1996), and in the metal poor stars of our Galactic halo.

Such a large fraction of Lyα lines with associated metal lines suggests that the intergalactic medium at $z \sim 3$ was enriched. The estimated metallicity in the Lyα systems depends on the value of the ionization parameter $\Gamma$.

Rauch, Haehnelt & Steinmetz (1996), however, compared the result of their numerical simulation with the observed data and estimated a mean metallicity of $Z \sim 10^{-2.5} Z_\odot$. 

\textsuperscript{*} Present address: Raman Research Institute, Bangalore 560080 India

© 0000 RAS
The IGM could have been enriched in a number of ways, e.g., Population III stars, early-forming very massive \((10^2 \text{ to } 10^5 \ M_\odot)\) objects (Carr, Bond & Arnett 1984) or galactic winds from galaxies at high redshifts. In this paper, we investigate the possibility that supernova-driven galactic winds from small star-forming galaxies at high redshift could have enriched the IGM. Such low-mass galaxies form naturally at high \(z\) in hierarchical clustering scenarios for galaxy formation, like CDM. If the gas in these galaxies can cool and form stars, then any metals produced when these stars go supernova can easily be ejected from the galaxy by supernova-driven winds, as the galaxies have shallow gravitational potential wells (Dekel & Silk 1986). This was in essence the scenario outlined by Couchman & Rees (1986), who consider the subsequent influence of these galaxies on structure formation. Here we investigate this scenario in detail, incorporating up-to-date cooling physics and compare our models to recent observations, concentrating on issues most directly related to metal production.

The amount of gas and the metallicity of the ejected gas from each galaxy depends on the mass of the galaxy and the parameters of star formation (e.g., Nath & Chiba 1995). The enriched gas would be carried in cooled shells which will propagate through the IGM, sweeping up matter. The shells (each with its own radius and metallicity, which have been fixed by the mass of the parent galaxy) will then collide and the enriched gas will be mixed. Given a long time, the gas will distribute more homogeneously and the resulting metallicity will depend on the mass function of galaxies, the redshifts when the galaxies erupted and the parameters of star formation (in addition to the cosmological parameters).

Several authors have commented on the production of metals as a possible by-product of astrophysical processes occurring during the early stage of galaxy formation (e.g. Fukugita & Kawasaki 1994, Voit 1996). Specifically, if supernovae are partly responsible for the generation of the UV background (particularly at soft energies; see Miralda-Escudé & Ostriker 1990, Madau & Shull 1996) and/or the reionization of the Universe (see Giroux & Shapiro 1996), then simultaneous cosmic metal production seems inevitable. Recently, Gnedin and Ostriker (1997) have presented the results of their numerical simulations of reionization and metal production at high redshift by Population III stars. Miralda-Escudé and Rees (1997) have discussed the production of metals by high redshift supernovae, but did not consider the details of the gas ejection dynamics and the mixing of the gas in the IGM. Even prior to these works, Silk, Wyse & Shields (1987) had contemplated on the enrichment of the IGM by bursting dwarf galaxies as a plausible cosmological process, continuing to the present day, along with the generation of the soft UV background.

This paper is structured as follows. In Section 2 we outline the chemical history of the Universe from the Big Bang to the present day, and place our model in this context and in the more general context of galaxy formation theories. In Section 3 we estimate the time evolution of the mean metallicity of the IGM. We also estimate its variance, from the details of the collisions between the shells and the consequent mixing of the gas. For simplicity, we assume a single epoch at which the galactic winds go off, assume the shocks to be spherical, and then model the evolution of the probability distribution of the IGM metallicity. We then compare this distribution with the observed metallicities of the Lyα clouds at \(z = 3\), the metallicity distribution of the metal-poor stars in the halo of our Galaxy, and other observations in Section 4.

2 THE CHEMICAL HISTORY OF THE UNIVERSE

In this section we outline a plausible scenario that describes the chemical history of the Universe. We do this so as to place the model we present here in the wider framework of the galaxy formation problem and also to highlight the observational contexts in which our results are and are not valid.

After the Big Bang, only hydrogen, helium, and trace amounts of lithium were present in the Universe; carbon and larger nuclei essentially did not exist. As the initial fluctuations in the dark matter spectrum grew, at some redshift, the very high \(\sigma\) peaks reached masses large enough that the baryonic component contained within these peaks may cool through molecular transitions (Blumenthal et al. 1984, Couchman & Rees 1986, Tegmark et al. 1997). The relevant baryonic mass scales vary from \(10^3\) to \(10^7\) \(M_\odot\) for \(100 > z > 10\) (see Figure 6 of Tegmark et al. 1997). The molecular hydrogen responsible for triggering the cooling mostly comes from \(H^+ + H^-\) interactions, where the \(H^-\) is made from \(H + e^-\) reactions (a small number of free electrons remain after recombination; Couchman & Rees 1986). No metals exist yet to assist in the cooling (however, see Gnedin & Ostriker 1992 for a possible alternative). After collapse is initiated and the densities get high \(H + H + H\) reactions presumably take over as the primary source of making \(H_2\). No dust grains are available so that absorption of \(H\) onto dust, which is the dominant method of making \(H_2\) in star-forming regions in the Milky Way, is not important. If sufficient \(H_2\) is made, the cooled baryons may form stars. If this happens, then some of these stars might become supernovae and produce some metals and UV photons. But at very high \(z >> 10\), these high \(\sigma\) objects are extremely rare, so that they do not produce significant amounts of metals (they may, however, reheat the IGM; Tegmark et al. 1997).

As the age of the Universe increases, the much more common lower \(\sigma\) peaks reach the mass scales required for the gas to cool, and baryonic collapse and possibly star formation becomes much more ubiquitous. It is this phase that we are concerned with in this paper. The mass scale here will be set mostly by atomic cooling, as molecular hydrogen will easily be photodissociated by the few UV photons produced by the few higher \(\sigma\) peaks (Haiman, Rees, & Loeb 1996). The main uncertainty preventing a rigorous study of this is the stellar initial mass function (IMF) in these galaxies, where the collapsing gas is essentially unenriched. We know that it is probably more biased to high masses than the local Salpeter IMF because otherwise at least 20% of halo stars would be pregalactic and made out of material that has only been processed once (i.e. during this phase; Miralda-Escudé & Rees, 1996). If this were true, then at least 20% of the halo stars would be heavy neutron-capture deficient (see Truran 1981, also Section 4.2), which is unlikely (Ryan, Norris &
Beers 1996). In this work, we adopt a parameterization that takes this lack of knowledge about the IMF into account.

Here we adopt plausible galaxy mass functions (from Press-Schechter (1974) theory), cooling efficiencies, and nucleosynthesis yields to compute the amount of metals produced. We then model the propagation of these metals by galactic winds through the IGM and compute the mean metallicity of the IGM and its spatial variance as a function of time. The mean value we get, about 0.01 Z⊙, compares well with the metallicities of the Lyα clouds seen at z = 3, and we conclude that the metals seen there could result from this phase of cosmic enrichment. In such a scenario, local star formation within the Lyα forest clouds themselves does not contribute many of the metals. This would not be surprising, as the systems are very small and diffuse (on the other hand, in the bigger, denser, and more metal-rich damped Lyα systems, self-enrichment almost certainly happens).

It is also probable that many of the lowest Z halo stars, in particular the Sr-deficient stars, might have been made from material that was only processed during this phase (see Section 4.2). Most of the rest of the halo probably came from material that was enriched by subsequent generations of stars that formed either in smaller stellar systems that were the Milky Way progenitors, or during the collapse of the halo (Eggen, Lynden-Bell & Sandage 1962). Another important consequence of the enrichment process is the generation of a large number of UV photons, which will raise the Jeans mass of the IGM, hence inhibiting further collapse of baryons into dark matter halos (e.g., Thoul & Weinberg 1995). What this means is that the redshift range over which this phase happens may be quite small (in this work we approximate it by a single characteristic value zmin). These UV photons may also in whole or part reionize the IGM (depending on the efficiency with which they can escape the galaxies), therefore explaining the H I Gunn-Peterson effect.

After this phase, star formation continues to happen in galaxies, although it may well have been suppressed (particularly in small galaxies; see Babul & Rees 1992, Efstathiou 1992) at z > 2 by the UV background produced by the galaxies described above, and by quasars at high redshift. Large numbers of star-forming galaxies are observed in the field (see e.g. Broadhurst, Ellis & Shanks 1988; Cowie, Songaila & Hu 1991), but these are typically more massive than the galaxies that are relevant in the preceding two paragraphs (Cowie, Hu & Songaila 1995). Therefore any metals produced are unlikely to escape the galaxies because of the deep potential wells. Galaxies like the Milky Way have also experienced considerable star formation in the disk and have retained the metals produced; this is why the disk stars and the local interstellar medium (ISM) have metallicities close to solar, much higher than the 0.01 Z⊙ produced in the phase above. Some of these galaxies may have since been tidally disrupted in interactions and the metals transferred from their ISM into the IGM. Because these galaxies might have had fairly metal-rich ISMs the IGM metallicity at z = 0 might be somewhat higher than 0.01 Z⊙; strong observational constraints on the z = 0 IGM metallicity do not exist at present. However, the Milky Way formed out of a gas cloud that was probably close to 0.01 Z⊙ in mean metallicity (this is inferred from the peak of the halo metallicity distribution function of Ryan & Norris 1991), so that the IGM was not probably significantly enriched above this value by the time the Milky Way formed.

The one case where the IGM metallicity at z = 0 is well known, is of course in galaxy clusters, where the hot intracluster medium (ICM) is metal-rich, with Z of 0.1 to 1 Z⊙. The measurement of the iron mass to optical luminosity ratio suggests that the cluster ellipticals provide these metals (Arnaud et al. 1992). The detection of Type II abundances with ASCA suggests that the metals come from Type II supernovae, which are not observed to occur in present-day ellipticals (Mushotzky et al. 1996, Loewenstein & Mushotzky 1996). This suggests that these ellipticals might have undergone a starburst phase early in their history (possibly an ultraluminous phase; see Sanders & Mirabel 1996), where substantial amounts of metals were made and which have since entered the ICM by cluster-related processes like ram-pressure stripping.

3 GALACTIC WINDS AND THE IGM

We will begin by explaining the different building blocks of our model — the galactic winds, their propagation in the IGM, and the interactions between the shells — and then compute the time evolution of the metallicity distribution.

3.1 Galactic winds

Galactic winds are believed to originate when the thermal energy of the interstellar gas in a galaxy exceeds its binding energy. The amount of gas and metals ejected by a galaxy of mass (including non-luminous matter) M depends on the parameters of star formation, νx, the IMF, star formation rate, and the efficiency of supernovae remnants in heating the ISM gas (Yoshii & Arimoto 1987). A variety of numerical works calculated the time for initiating the galactic wind and the metal enrichment as a function of these parameters (see, e.g., Matteucci & Gibson 1995 and references therein). We will use the results of Nath & Chiba (1995), which are based on simple assumptions, but are close to those obtained from more sophisticated approaches, for our purpose.

Nath & Chiba (1995; hereafter NC95) estimated the fraction γ of the galactic mass M ejected in a wind (Mwind = γM) (their equations (10) and (14)), and the metallicity of the ejected gas, Zwind (their eqn (9)), using iron as the trace element. The total amount of metals ejected from each galaxy is then ZwindMwind. These values depend on the slope of the IMF (ϕ(m) ∝ m−x dm, x = 1.35 for Salpeter IMF) and the efficiency of the supernova remnants in heating up the ISM gas (η ∼ 0.1). They incorporated the IMF slope, the upper and lower limits of masses of main sequence stars and the lower limit of the mass of stars which go supernova, into a single parameter ν50, which was defined as the number of supernovae per 50 M⊙ of baryons. For a Salpeter IMF, x = 1.35, ν50 ∼ 0.37 (for details see NC95). The important concept here is that γ and Zwind are single-valued functions of M given ν50 and η (typical examples of these functions are given in Figure 1 of NC95). Consequently, the functions γ(M) and Zwind(M), combined with the mass function of the galaxies, yield the total amount of metals produced.
The total energy in the explosion (meaning the cumulative effect of all the supernovae in a galaxy) is uncertain and we adopt the method of Tegmark, Silk, & Evrard (1993, hereafter TSE93) to estimate this. We need to know this number because it determines how well the winds and the metals they carry are propagated through the IGM. Since the galactic winds last for $t_{\text{SN}} \sim 5 \times 10^7$ yr, which is much smaller than any other timescales in this calculation, we assume them to be ejected in an explosive manner. Making this assumption, the total energy in the galactic wind is then $0.02 \times 0.007 \times M_\odot c^2$, where $M_\odot$ is the baryonic mass in the galaxy. The 0.02 comes from the observations of Heckman, Armus, & Miley (1990) who show that 2% of the total luminosity of high-z starburst galaxies goes into galactic winds. If one assumes the galactic wind to have a constant mechanical luminosity $L_{\text{mech}}$ for the duration of $t_{\text{SN}}$, then TSE93 show that $L_{\text{mech}} \sim (M_\odot/M_\odot) L_\odot$. In the calculations below, we assume $M_\odot = 0.1 M_\odot$ (we discuss the effect of the uncertainty in this relation on the final results in §4).

3.2 Propagation of galactic winds in the IGM

We will again follow TSE93 in calculating the propagation of the galactic winds in the IGM. The matter in the wind is assumed to be in a dense, cool shell (except for a small fraction of mass in the hot interior), that is sweeping more mass from the IGM. The density of particles in the shell can be estimated by equating the ram pressure ($m_p n_a V_{sh}^2$, where $n_a$ is the ambient particle density and $V_{sh}$ is the shock velocity) to the thermal pressure of the gas in the shell, which is assumed to be cold (at $T \sim 10^4$ K, the lowest temperature attained by gas in the absence of molecular cooling). This gives the particle density in the shell, $n_s = n_a 120 V_{sh,100}^2$, where the shock velocity is written in the units of 100 km/s. Assuming the total mass inside the radius $R$ of the shell to be contained within the shell, the thickness of the shell is $\delta R = (R/360) V_{sh,100}^{-2}$.

Let the pressure inside the shell be $p$, which is driving the shell outward with a force $4 \pi R^2 p$. The sweeping of matter from the IGM provides a braking force equal to $(\dot{R} - H R) \rho_{\text{IGM}} = (\dot{R} - H R) \times 3(1/3 - H)$, where $H$ is the Hubble constant. There is another braking force due to the gravitation of mass in the shell. If the dark matter density (in units of the critical density) is $\Omega_d$, then the equation of motion of the shell is (eqn (1) of TSE93) given by

$$\dot{R} = \frac{8 \pi G \Omega_{\text{IGM}} H^2 R}{3 R (\dot{R} - H R)^2 - (\Omega_d + 0.5 \Omega_{\text{IGM}}) (0.5 H^2 R)}.$$  

(1)

Here, $\Omega_{\text{IGM}}$ is the ratio of the density of the intergalactic gas to the critical density. This should be differentiated from the total baryon density in the universe, $\Omega_b$ (expressed in the units of the critical density), as some of the baryons would be in the collapsed halos and not in the intergalactic medium.

The evolution of the total energy inside the shell $(E_t = \frac{3}{2} p V^2 = 2 \pi p R^3)$ is given by (TSE93)

$$\frac{dE_t}{dt} = L_{sn} - 4 \pi p R^2 \dot{R} - L_{\text{brem}} - L_{\text{comp}}.$$  

(2)

Here, the first term refers to the energy input due to supernovae, the second term is due to adiabatic loss, the third term describes energy loss due to free-free radiation and the last term is the energy loss rate due to inverse Compton scattering off the microwave background photons.

We solve the above two equations for the propagation of the shells in the IGM. For the initial conditions, we assume that the initial radius of the shell is the radius of the galaxy. We adopt the scaling of Saito (1979) for the typical size of a galaxy ($R = 1.2 \times 10^7 (M/10^{12} M_\odot)^{0.55}$ kpc). The initial velocity is expected to be of the order of the thermal velocity of the ISM gas which is presumably heated to $\sim 10^6$ K (Babul & Rees 1992), i.e. $V_{sh,100} \sim 1$ initially. However, we found that the results are almost independent of the initial velocity, as the kick due to $L_{sn}$, which we assume to continue for $5 \times 10^7$ yr, basically determines the propagation of the shell.

The upper two panels of Fig. 1 show the evolution of the radius and velocity of the shell ejected from galaxies with masses $10^8$ and $10^9 M_\odot$ at redshifts 1 and $z_{\text{SN}} = 5$ and 7.

3.3 Porosity

If the comoving mass function of the parent objects which ejected their galactic winds at a certain redshift, $z_{\text{SN}}$, is $n(M, z_{\text{SN}})$ (which has the dimensions of $\text{Mpc}^{-3} M^{-1}$) then the porosity $\text{por}$ of the IGM at some later redshift can be defined as

$$\frac{d}{dM}\text{por}(M, z, z_{\text{SN}}) = \frac{4 \pi}{3} R(M, z, z_{\text{SN}})^3 n(M, z_{\text{SN}}) \left( \frac{1 + z_{\text{SN}}}{1 + z} \right)^3.$$  

(3)

The porosity here simply denotes the filling factor of the spherical shocks (volume $\times$ number density of parent objects) for $\text{por} \leq 1$. For larger values of $\text{por}$, the shells over-
lap one another, and in this case, the filling factor of the overlapped regions is $1 - \text{por}^{-1}$. The function $n(M, z_{\text{in}})$ can be estimated for a given model of structure formation from Press-Schechter theory.

The Press-Schechter mass function only refers to objects with a density contrast above a threshold value. To be specific, it counts objects with linearly extrapolated overdensity $\delta(1 + z) > \delta_c(1 + z_c)$, where $z_c$ is the collapse redshift. To form a galaxy by a given $z$ the gas in the halo must, in addition to reaching some threshold density contrast, cool within a Hubble time $t_H(z)$. We take this effect into account using the approach of Peacock & Heavens (1990). They showed that the effect of cooling can be taken into account by changing $(1 + z_c)$ in the Press-Schechter mass function to $(1 + z)(1 + M/M_{\text{cool}})^{2/3}$, for galaxies to have formed by a given redshift $z$, where

$$M_{\text{cool}} \sim 3.6 \times 10^{11} \left(\frac{\Omega_b}{0.05}\right) M_\odot;$$

(4)

here we use the nucleosynthesis value of $\Omega_b \sim 0.05 h_{50}^{-2}$ ($h_{50}$ is the Hubble constant in units of 50 km s$^{-1}$ Mpc$^{-1}$) and we have assumed cooling in the absence of metals. We use this function for our calculations below.

Formally, we should extend the above calculations to include the constraint that not only should the galaxy form, but it should also have had enough time for the supernovae to heat up the ISM and for the galactic wind to ensue. However, we find that, for reasonable parameters of star formation ($\nu_{\text{SN}} = 0.35, \eta = 0.1$), the ratio of the time scale for galactic winds ($t_{\text{gw}}$, see NC95) and the cooling time of the gas $t_{\text{cool}}$ is

$$\frac{t_{\text{gw}}}{t_{\text{cool}}} \lesssim 2 \left(\frac{M}{10^9 M_\odot}\right)^{-0.225} \left(\frac{(1 + z)}{6}\right)^{3/2},$$

(5)

where we have assumed primordial cooling (Peacock and Heavens 1990), $\Omega_b = 0.05$ and $h_{50} = 1$. The two time scales are of the same order for the range of masses we are interested in. Therefore, the additional constraint ($t_{\text{cool}} + t_{\text{gw}} \leq t_H$) will not substantially change the above mass function, and so we neglect it here.

As a template model of structure formation, we use the standard CDM (hereafter sCDM) model with $h_{50} = 1$ and $\Omega = 1$. We use the normalization of $\sigma_8 = 1.2$ from the analysis of COBE data of four years (Bunn & White 1996). We use the analytical fit to the CDM power spectrum as given in White & Frenk (1991) for our calculations.

In the lower panel of Fig. 1, we plot the porosity as a function of redshift for $M = 10^8$ and $10^9 M_\odot$ for $1 + z_{\text{in}} = 5, 7$ in the sCDM model, calculated by integrating eqn (3) with $n(M') \propto \delta(M' - M)$. The important thing to note in the figure is that shells from more massive galaxies reach the unit porosity limit later in time.

### 3.4 Metallicity of the shells

The metallicity of the shells will depend on (a) the amount of metals ejected by the parent galaxy ($M_{\text{wind}}$, see above in §3.1), (b) the total amount of gas ejected ($M_{\text{wind}}$), and (c) the amount of IGM gas swept up by the shell ($(4\pi/3)R^2\rho_{\text{IGM}}$, assuming that it has not collided with any other shells so far; otherwise see below). The metallicity of the shell in this case is then given by

$$Z_{\text{shell}} = \frac{M_{\text{wind}} Z_{\text{wind}}}{M_{\text{wind}} + (4\pi/3)R^2\rho_{\text{IGM}}}. \quad (6)$$

If the enrichment of the IGM is absolutely homogeneous, then the total metallicity of the IGM will be

$$Z_{\text{IGM, hom}}(z_{\text{in}}) = \frac{\int M_{\text{wind}} Z_{\text{wind}} n(M, z_{\text{in}}) dM}{\int M_{\text{wind}} n(M, z_{\text{in}}) dM + \rho_{\text{IGM}}}, \quad (7)$$

and so we neglect it here.

The metallicity of the shells will then also be estimated for a given model of structure formation from Press-Schechter theory.

When galaxies merge, the result of each interaction will depend on the velocity of the shells involved. With the assumption of a single $z_{\text{in}}$ for all galactic winds, one can make a one-to-one correspondence between the velocity of the shell and the mass of the parent galaxy, and this makes it simpler to trace the evolution of the shells, as explained below.

The interactions between the shells are very complicated in general. It will be useful here to divide them into two categories. The first type of interaction is that between shells of different sizes. For simplicity, let us assume that the interacting shells differ greatly in their sizes ($R_3 \ll R_2$, at some redshift $z$). In the approximation of a single epoch of galactic winds, as the curves in Fig. 1 show, the corresponding velocities are then also very different, with $V_3 < V_2$. It is then also true (from the same curves) that the masses of the parent galaxies and therefore the metallicity of the shells are different: $Z_{\text{shell},1} \ll Z_{\text{shell},2}$.

We assume that in this case, the shell with larger velocity and momentum (and therefore, with higher metallicity) will sweep the matter in the other shell with it. Let us look at the shells of size $R_2$. Shells of much smaller size $R_1 \ll R_2$ would have attained unit porosity much earlier than these shells. In other words, by the time the shells of size $R_2$ have reached a reasonably large size, shells of much smaller sizes would have overlapped and distributed their metal enriched gas homogeneously in the IGM. For shells which have reached a size $R_2$ at some redshift, the IGM gas already has a metallicity corresponding to shells of smaller sizes, originating from smaller galactic masses, that is, $Z_{\text{IGM, hom}}(M' < M_2, z_{\text{in}})$, where $R_2$ is the size of the shell from a parent galaxy of mass $M_2$. Although, strictly speaking, this is true only for $R_2 \gg R_1$, for analytical sim-
fig. 1) that shells from more massive galaxies reach the unit porosity limit later in time. Consider now the shells corresponding to mass (of parent galaxies) $M_i$. Once the porosity of these shells reach unity, the IGM gas, including the gas and metals from shells corresponding to $M < M_i$, has been more or less raked up by these shells. This means that $Z_{\text{shell},M}$ does not increase any longer. Therefore, we freeze the metallicity of the shells once they reach unit porosity, and keep it constant during their evolution later.

Fig. 2 shows the curves for $Z_{\text{shell},M}$ as a function of $M$ at different redshifts, for $1 + z_{\text{in}} = 10$. In general, the shell metallicity decreases in time because of sweeping more and more of IGM gas, which must have lower $Z$. At later times (small $z$), the curves, therefore, flatten out. Note that, after reaching unit porosity, the shell metallicity does not change, giving rise to the envelope of the curves at the left hand side of Fig. 2.

The second type of interaction takes place between shells of similar sizes ($R_1 \sim R_2$). This type of collisions in general gives rise to two reflected shockwaves moving away from the plane of intersection, two contact discontinuities and another shock wave forming an annulus where the shells intersect. For simplicity, we neglect the annulus here. Furthermore, for geometrical simplicity, we assume that the region bounded by the reflected shockwaves can be reproduced by imagining the colliding shells passing through each other, since the reflected shocks have similar velocities as the original shells (see, e.g., Voinovich & Chernin 1995). The matter in this region is compressed and heated twice by the reflected shocks to a temperature $\sim 6 \times 10^4$ K, for a typical shell velocity $V_{\text{sh}} \sim 50$ km/s (see Fig. 1). The sound velocity of the gas at this temperature is $\sim 30$ km s$^{-1}$. We assume that this gas fills up homogeneously the region bounded by the reflected shocks (or, in our oversimplified picture, by the shells continued through each other). This is shown schematically in the right panel of Fig. 3. Let us call this assumption A2. We note here that, this is strictly true only for shocks which do not have cold shell; in the case of cold shells, the gas forms a ring (Yoshika & Ikeuchi 1990).

### 3.6 The probability distribution of metallicity

Let us consider the galaxies of mass $M$. At some redshift $z < z_{\text{in}}$, the galactic wind shells from these galaxies have radii $R$. If the porosity for only these shells (as defined in §3.3) is less than unity (Case I in Figure 3), then these shells will have mostly collided with shells of smaller size, which are more numerous than shells of size greater than or equal to $R$. The shell will therefore have a metallicity $Z_{\text{shell},M}$ given by eqn (9) above (because of assumption A1). Since the gas is accumulated in the shell of thickness $\delta R$, the filling factor of the gas of metallicity $Z_{\text{shell},M}$ is $[(3R/R)\text{por}(M,z,z_{\text{in}})]$. We could tentatively equate this as the probability of the IGM gas to have a metallicity $Z = Z_{\text{shell},M}$. However, because of assumption A1, we note that the shells of size $R$ will also be pushed around by shells of larger size, and therefore, be mixed with higher metallicity gas (since $Z_{\text{shell},M}$ is an increasing function of $M$, or equivalently $R$; see Fig. 2). Strictly speaking, then, the above filling factor will equal the probability that the intergalactic gas has metallicity $Z$ or higher. Let us call this quantity $p(> Z)$.

If the porosity is larger than unity (Case II in Figure 3), then the filling factor of the gas with metallicity $Z = Z_{\text{shell},M}$ at redshift $z$ is simply $1 - (1/\text{por}(M,z,z_{\text{in}}))$, from assumption A2. Again for the above reasons, we will equate this to $p(> Z)$. 

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{The shell metallicity, $Z_{\text{shell},M}$, is shown as a function of the galactic mass $M$ at different redshifts, for $1 + z_{\text{in}} = 10$. In the sCDM model and $\Omega_{\text{GM}} = 0.05$.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{The two limits of calculating the filling factor of gas of a given metallicity are shown schematically. In Case I, the gas with the metallicity $Z_{\text{shell},M}$ is confined within the shells originating from galactic mass $M$. In Case II, the gas occupies the overlapping regions. Note that the structure of shocks in the interacting region is very simplified here (see text).}
\end{figure}
We can then consider galactic winds from galaxies of different masses, calculate the shell metallicities \( Z = Z_{\text{shell,M}} \) at each redshift, and calculate the function \( p(> Z) \) using the algorithm described above, depending on the value of the porosity for these shells. This function is essentially \( p(> Z) = \int_0^Z p'(Z')dZ' \), where \( p'(Z') \) is the probability distribution function of the IGM metallicity.

4 RESULTS AND DISCUSSIONS

We plot in the left panels of Fig 4a, 4b and 4c, the function \( p(> Z) \) at various redshifts for the cases \( 1 + z_{\text{in}} = 10, 7, 5 \). We assumed \( \Omega_{\text{IGM}} = 0.05, \nu_{\text{SN}} = 0.37, \eta = 0.1, \) and sCDM model (with \( \Omega = 1, h_{\text{eq}} = 1 \)). The right panels show the the mean and the standard deviation as a function of the redshift for the three cases. The dashed line in the right panels show the values of \( Z_{\text{IGM, hom}} \), i.e., the metallicity of the IGM if the metals were distributed homogeneously. It is seen that the mean metallicity increases in time to approach this value.

A note on the uncertainties involved in the calculations is in order here. We have done the calculations for other values of the parameters \( \Omega_{\text{IGM}} \) and \( L_{\text{SN}} \). Changing the value of \( \Omega_{\text{IGM}} \) to 0.01, increases the shell metallicities, and shifts the curves horizontally by at the most 0.3 dex. Decreasing \( L_{\text{SN}} \) by a factor of two, decreases the metallicities by \( \sim 0.15 \) dex.

4.1 Comparison with the metallicity of Ly\( \alpha \) systems

The reported metallicity of the Ly\( \alpha \) systems at \( z \sim 3 \) is \( Z/Z_{\odot} \sim 10^{−2.5}−10^{−2} \) (Rauch et al. 1996, Cowie et al. 1995). Fig 5 shows the mean metallicity and the standard deviation at \( z = 3 \) in our model, as functions of \( z_{\text{in}} \). Curves are shown for \( \Omega_{\text{IGM}} = 0.01 \) and 0.05. The figure shows that our model conforms to the observed values of the mean metallicity of the Ly\( \alpha \) absorption systems at \( z \sim 3 \) if \( z_{\text{in}} \lesssim 5 \), considering both the observational and our theoretical uncertainties.

It should be noted here that the determination of metallicity in the Ly\( \alpha \) absorption systems depends on the assumed value of the ionization parameter \( \Gamma \) – the ratio of the density of ionizing photons to that of the particles in the Ly\( \alpha \) systems—which is uncertain. The resultant metallicity measured is then uncertain to about a factor of two. It is hoped that future observations (including those of other elements than carbon) will give better values of the metallicity and its scatter, so that the above model can be tested against the data. In addition, abundance anomalies that are seen in the Ly\( \alpha \) forest may yield important information about the masses of the stars that are producing the supernovae (Woosley & Weaver 1992), which in turn will allow better nucleosynthesis yields to be used in predicting the metallicities, in addition to information about \( \Gamma \).

4.2 Comparison with the metallicity of halo metal poor stars

It is well known that there exist in the Milky Way halo a few stars with much lower \( Z \) than we would expect given the metallicity of the initial gas cloud out of which the Galaxy formed. Six stars with \( Z < 0.001 Z_{\odot} \) exist in the complete sample of Ryan & Norris 1991 (hereafter RN91 – see their Fig. 5d); the lowest metallicity star known is the carbon star G66−71, which has \( Z \sim 10^{−5.5} Z_{\odot} \) (Gass, Liebert & Wehrse 1988). The mean metallicity of halo stars is about \( Z \sim 10^{−1.5} Z_{\odot} \) (RN91). Such large inhomogeneities might not have existed within the primordial gas cloud that was originally the Milky Way and are not required by this model (however they are not inconsistent with observation; RN91). The most natural interpretation is that these stars are pre-
galactic and dynamically are associated with the dark matter, and not the rest of the stellar halo (however, binary mass transfer effects, like differential absorption of elements onto dust, might be important in explaining the low metallicities of extremely low-Z carbon stars like G66–71). We now investigate this possibility.

A very approximate quantitative analysis is suggested. Although the probability distribution functions calculated above are not Gaussian, let us discuss the case of a Gaussian distribution, for the sake of illustration. In our model, where the IGM metallicity has a mean and spatial variance of 0.01 Z⊙, we would expect 18% of all pregalactic stars to have Z < 0.001 Z⊙. Here “pregalactic” refers to stars that formed out of material processed only through the phase described by this model and also to any stars that might represent the low-mass tail of the IMF described in Section 3; stars that formed from gas that had been enriched further in smaller galaxies that were Milky Way progenitors are excluded. As 6 stars in the RN91 sample satisfy this constraint, we would then estimate that 32 stars in their sample are pregalactic of which 16 would have Z < 0.01 Z⊙. This is 16% of the total number of stars (104) in the RN91 sample with Z < 0.01 Z⊙, which in turn suggests 16% of the stars in the halo with Z < 0.01 Z⊙ are pregalactic. If one takes all the stars in the RN91 sample (372), then one finds 32/372 = 9% of all halo stars to be pregalactic. The rest of the stars formed during collapse of the halo, or in MW progenitors.

So it is natural in our model that these stars should exist. Our model also predicts the existence of a few very low Z stars like G66–71 (although in this case binary mass transfer is the more plausible explanation, particularly in light of the inverted C/O abundance; Gass, Liebert & Wehrse 1988). Surveys of the low Z halo stars, including both proper motion surveys like RN91 and objective prism surveys, are rapidly getting larger, and a metallicity probability distribution function for the Galactic halo should soon be available with much better statistics at the low Z end than that in RN91. Then the calculation in the previous paragraph may be done rigorously. This will provide one of the strongest constraints on the model presented here, and more generally on models that seek to explain the origin of the metals in the IGM.

The pregalactic stars, as defined above, should have r−2 density profiles, like the dark matter, not r−3 profiles, like most of the stellar halo (Rees 1997). Recent analysis of point-sources in the Hubble Deep Field (Elson, Santiago & Gilmore 1996) suggest that if the Milky Way has an extended stellar halo, this extended halo must be very small compared to the rest of the halo. This suggests that the fraction of halo stars that are pregalactic is very low, and that our estimate earlier in this section is too high. This prediction will not, however, be testable for some time because surveys of low Z stars would need to be carried out over regions well outside the solar neighborhood, where most stars are very faint. The best chance of making this measurement in the future is if we can identify a population of horizontal branch stars that are likely to be pregalactic based on metallicity and abundance ratio considerations.

Another potentially powerful probe of the properties of pregalactic stars involves heavy neutron-capture element (e.g. strontium = Sr) abundances (see Truran 1981, also Magain 1989; Ryan, Norris, & Bessell 1991). In the scenario described by these authors, the first generation of stars (i.e. that described in this paper) only synthesizes iron peak nuclei from the unenriched gas. The second generation performs secondary neutron capture. Only third or later generation stars would then have the heavy neutron-capture elements. This would in turn mean that any primordial stars should be deficient in these elements. So would be any second generation stars, which are also among the ones we call “pregalactic” here. The most detailed survey of Sr abundances comes from Ryan, Norris, & Beers (1996). Lower metallicity stars do tend to have less strontium. However, the evidence suggests that very few indeed, if any, are completely Sr deficient. Again, this means that the pregalactic fraction of halo stars that we estimated above is probably too high. It also means that the IMF in the galaxies in Section 3 is probably biased towards higher masses (if it was Salpeter, then at least 20% of halo stars would have been pregalactic (specifically first-generation); Miralda-Escudé & Rees 1997). An important caveat is that accretion of material (in this case Sr) from the ISM onto the atmospheres of the halo stars is small (see Yoshii 1981), so that the Sr-deficient population we observe is the true primordial one.

4.3 Constraints from the UV background radiation

Gunn-Peterson tests show that the IGM was highly ionized by z ∼ 5. Several models for the reionization of the IGM have been discussed in the literature, especially those investigating photoionization by various sources (quasars, star forming young galaxies, decaying neutrinos). Shapiro & Giroux (1987; see also Giroux & Shapiro 1996) claimed that ionizing photons from the observed quasar population were not enough for reionizing the IGM. Miralda-Escudé & Ostriker (1990) showed that including the UV photons from the star forming galaxies at high redshift would make the spectrum of the UV background radiation softer.

The UV background radiation at high redshift has been estimated using the proximity effect (Bajtlik, Duncan & Os-
trioker 1988). It is known that the intensity of the UV background at the Lyman limit is \( \sim 10^{-21} \text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1} \) at \( z \sim 2-3 \), although the value at higher redshifts remains uncertain (see, e.g., Bechtold 1994; Cristiani et al. 1996). Gunn-Peterson tests for both H I and He II atoms at high redshift give clues to the spectrum of the UV background radiation. The recent observations of He II absorption at \( z \sim 3 \) (see e.g. Songalia, Hu & Cowie 1995) have been used to further constrain the spectrum. Madau & Meiksin (1994) showed that the observed constraints allowed several possible sources, ranging from only observed quasars to a combination of quasars and star forming galaxies.

Star formation responsible for the galactic winds at high redshift discussed above would necessarily produce UV photons, and might reionize the IGM at high redshift. Silk, Wyse & Shields (1987) suggested that early galactic winds from dwarf galaxies would enrich the IGM and could also provide a soft UV background radiation. Miralda-Escudé & Ostriker (1990) noted that the intensity of the radiation is consistent with a cosmic metallicity of \( \sim 0.01 \) solar. Giroux & Shapiro (1996) considered the problem of metal production in galaxies responsible for photoionization of the IGM in detail. They showed that the metal enrichment inside the galaxies could reach 20%–30% of solar metallicity by \( z \sim 3 \) if the metals are not ejected from the parent galaxies.

Madau & Shull (1996) considered the metal production rate in star forming galaxies at high redshift. They did not however consider physical processes that might distribute the metals outside the parent galaxies; their models differ fundamentally from ours in that they assume that the metals observed in the Ly\( \alpha \) clouds at \( z = 3 \) were made inside those clouds. They considered continuous metal production in galaxies from \( z \gtrsim 4 \) and determined the resulting UV background radiation at \( z \sim 3 \), after letting the UV photons traverse the cloudy IGM. For continuous star formation from \( z = 4 \), and for reaching a metallicity of 0.01 solar in the parent galaxies by \( z = 3 \), the resulting UV background radiation has an intensity (at the Lyman limit) of \( 0.13 \times 10^{-21} \text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1} \). This assumes that a fraction \( f_{\text{esc}} = 0.25 \) of the UV photons escapes the parent galaxies. This value of the intensity is small compared to that estimated from proximity effect (see above). The important concept stressed by these authors is that \( f_{\text{esc}} \) is very poorly known (see also Leitherer et al. 1995, and the discussion of that paper in Madau & Shull 1996, for observational constraints). In addition, the IGM itself might have considerable opacity at \( z > 5 \) (no Gunn-Peterson constraints exist), and this might also reduce the contribution of the UV photons produced to the cosmic background.

In our model, the galaxies emit their UV photons at higher redshifts than considered by Madau & Shull (1996). Given their calculations, the contribution of these photons to the UV background at \( z \sim 3 \) must be even less than produced in their \( 3 < z < 4 \) continuous star-formation model. Given this, and the uncertainties above, it seems reasonable to state that the UV background we produce is likely to be significantly smaller than what is observed through the proximity effect.

4.4 Can we see this process in progress?

The brightest objects at \( z_{\text{in}} \) will be the supernovae that produce the metals here. They will have \( K \sim 27 \) at \( z = 5 \) (duration \( \sim 1 \) year) in the observer frame, which is too faint to see from the ground (Miralda-Escudé & Rees, 1997).

An interesting idea suggested by Miralda-Escudé & Rees (1997) is that a few of these high-\( z \) supernovae will happen to fall behind rich clusters of galaxies and so have their total flux amplified by gravitational lensing. The cross-section that they estimate for magnifying a source by more than \( A = 100 \) is about \( 10^{-4} \) arcminutes (this is the minimum magnification for such an object to be detected at present). This suggests that the probability of seeing such an object in any given rich cluster at a given time is 0.01%. If we surveyed 100 clusters to \( K = 22 \) every year, we would then have a 1% chance of finding one of these SN. As sensitive K-band detectors become available on large telescopes, lower A events become detectable and this project becomes feasible (optical detection is unlikely because observer-frame optical wavelengths probe rest-frame UV wavelengths, where supernovae are intrinsically faint).

The discovery of such an object should be straightforward to confirm spectroscopically, unless its \( z \) is so high (\( z > 10 \)) the strongest emission lines get redshifted too far into the infrared, where such faint-object spectroscopy is impossible.

4.5 What is the fate of the small galaxies?

In our model, the galaxies responsible for producing the metals had their baryons blown out by the galactic winds (Dekel & Silk 1986). Therefore, if they survive to the present day, they must be almost dark, unless they have undergone recent infall of gas from the IGM and made more stars (this is the scenario described by Silk, Wyse, & Shields 1987). A few almost dark, low-mass galaxies are known in the Local Group. The most extreme examples are Carina (Mateo et al. 1993), Draco, and Ursa Minor (Pryor & Kormendy 1990). Galaxies like Draco and Ursa Minor have stellar populations that are not self-gravitating and are \( > 99% \) dark matter by mass within their core-fitting radius. Their total dark-matter fractions depend on the mass distribution outside this radius, and will probably be higher still. These galaxies are the natural remnants of the process described in this paper. The few stars that they do have probably result from later gas infall and subsequent star-formation. They do not have zero metallicity (Hodge 1989) so do not represent the low-mass tail of the IMF described earlier in this paper. Very few low-mass first-generation stars, if any, exist in these galaxies (a similar low-mass star deficient mass function has been suggested for the Galactic halo; Nakamura Kan-ya & Nishi 1997).

But these galaxies do not exist in large number. The galaxy luminosity function in the Local Group (van den Bergh 1992) is certainly not increasing rapidly at \( M_B \sim -7 \), the luminosity of Draco & Ursa Minor.

So where have the galaxies that produce the metals gone? Many might have undergone considerable subsequent gas infall (as argued in Silk, Wyse & Shields 1987) and so be luminous galaxies today. They may even have merged with larger galaxies, or even have been tidally disrupted. Draco,
Ursa Minor, and Carina, if they really are remnants of the present model, would then be anomalous in that they had not suffered any of these fates

An alternative is that more recent gas infall has not happened in most remnants of the present process, and that there exist many undetected dark galaxies today. Draco and Ursa Minor would then be anomalously bright examples of these objects, where the little amount of gas they picked up allowed them to form a few stars, which in turn allowed them to be detected.

4.6 The origin of the X-ray emitting gas in clusters

Presumably the X-ray emitting gas that is now seen in clusters has experienced the process described in this paper (although the galaxies here are not the source of most of the ICM metals; see Section 2). In two previous papers (Trentham 1994, NC95), we argued that dwarf galaxies might contribute much of the ICM. In the context of the present model, much of the IGM might well have been processed in small galaxies, but these are very different systems from the present-epoch cluster dwarf galaxy population discussed in those papers.

4.7 Concluding remarks

To summarize, we have found that galactic winds at high z could have enriched the IGM to a mean metallicity of $Z \sim 0.01Z_\odot$ at $z \sim 3$, with a standard deviation of the same order, if $z_{\text{HI}} \lesssim 5$, and that this satisfies all the observational constraints.

While our results show that these kinds of processes can easily account for the observed IGM metallicity, we needed to make a number of simplifying assumptions and adopt convenient but plausible values for our model parameters. This work has been presented mostly in the spirit of a plausibility argument, and we have not attempted a detailed study of parameter space. Numerical investigations will hopefully provide more insight into this process and will allow an assessment of the permissible ranges for the input parameters in models like the present one. These will provide important constraints on galaxy formation theories.

Additional observations will also provide stronger constraints. Specifically, measurements which should be particularly valuable are (i) measurement of abundances ratios in the Lyo forest, (ii) the metallicity distribution function of the Galactic halo for a large sample of stars, and (iii) heavy neutron-capture elemental abundances for an equally large sample.

B.N. thanks Drs. M. Chiba, P. Biermann and N.T. thanks Drs. L. Cowie, J. Norris, and M. Rees for stimulating discussions. The authors also thank the anonymous referee for his comments.

REFERENCES

Arnaud, M., Rothenflug, R., Boulade, O., Vigroux, L., & Vangioni-Flam, E. 1992, A&A, 254, 49
Babul, A., & Rees, M. J. 1992, MNRAS, 255, 346
Bajtlik, S., Duncan, R. C., & Ostrik, J. P. 1988, ApJ, 327, 520
Bechtold, J. 1994, ApJS, 91, 1
Blumenthal, G. R., Faber, S. M., Primack, J. R., & Rees, M. J., 1984, Nature, 311, 517
Broadhurst, T. J, Ellis, R. S, & Shanks, T. 1988, MNRAS, 235, 827
Bunn, E. F., & White, M. 1996, preprint (astro-ph/9607060v2)
Carr, B. J., Bond, J. R., & Arnett, W. A. 1984, ApJ, 277, 445
Couchman, H. M. P., & Rees, M. J. 1986, MNRAS, 221, 53
Cristiani, S., D’Odorico, S., Fontana, A., Giallongo, E., & Savaglio, S. 1995, MNRAS, 273, 1016
Cowie, L. L., Hu, E. M., & Songaila, A. 1995, Nature, 377, 603
Cowie, L. L., Songaila, A., & Hu, E. M. 1991, Nature, 354, 460
Cowie, L. L., Songaila, A., Kim, T. S., & Hu, E. M. 1995, AJ, 109, 1522
Dekel, A. & Silk, J. 1986, ApJ, 303, 39
Efstathiou, G. 1992, MNRAS, 256, 43p
Eggen, O. J., Lynden-Bell, D., & Sandage, A. R. 1962, ApJ, 136, 748
Elson, R. A. W., Santiago, B. X & Gilmore, G. F. 1996, New Astron., 1, 1
Fukugita, M., & Kawasaki, M. 1994, MNRAS, 269, 563
Gass, H., Liebert, J., & Wehrse, R. 1988, A&A, 189, 194
Giroux, M. L., & Shapiro, P. R. 1996, ApJS, 102, 191
Gnedin, N. Y., & Ostrik, J. P. 1992, ApJ, 400, 1
Gnedin, N. Y., & Ostrik, J. P. 1997, preprint (astro-ph/9612127)
Haiman, Z., Rees, M. J., & Loeb, A. 1996, preprint (astro-ph/9608130)
Hodgkin, T. M., Armus, L., & Miley, G. K. 1990, ApJS, 74, 833
Hodge, P. W. 1989, ARAA, 27, 139
Leitherer, C., Ferguson, H. C., Heckman, T. M., Lowenthal, J. D. 1995, ApJ, 454, L19
Loewenstein, M., & Mushotzky, R. F. 1996, ApJ, 466, 695
Lu, L., Sargent, W.L.W., & Barlow, T.A. 1996, preprint (astro-ph/9606044)
Madau, P., & Meiksin, A. 1994, ApJ, 433, L53
Madau, P., & Shull, J. M. 1996, ApJ, 457, 551
Magain, P. 1989, A&A, 209, 211
Mateo, M., Olszewski, E. W., Pryor, C., Welch, D. L., & Fischer, P. 1993, AJ, 105, 510
Matteucci, F., & Gibson, B. K. 1995, A&A, 304, 11
Meyer, D. M., & York, D. G. 1987, ApJ, 315, L5
Miralda-Escudé, J., & Ostrik, J. P. 1990, ApJ, 359, 1
Miralda-Escudé, J., & Rees, M. J. 1997, ApJ, in press (astro-ph/9701093)
Mushotzky, R. F., Loewenstein, M., Arnaud, K. A., Tamura, T., Fukazawa, Y., Matsushita, K., & Hatsukade, I. 1996, ApJ, 466, 686
Nakamura, T., Kan-Ya, Y. & Nishi, R. 1997, ApJ, 473, L99
Nath, B. B., & Chiba, M. 1995, ApJ, 454, 604 (NC95)
Peacock, J. S., & Heavens, A. F. 1990, MNRAS, 243, 133
Press, W.H., & Schechter, P. 1974, ApJ, 187, 425
Press, W.H., & Schechter, P. 1974, ApJ, 187, 425
Ryan, S. G., Norris, J. E., & Bessell, M. S. 1991, AJ, 102, 303
Sanders, D. B., & Mirabel, I. F. 1996, ARAA, 34, 749
Shapiro, P. R., & Giroux, M. L. 1987, ApJ, 321, L107
Silk, J., Wyse, R. F. G., & Shields, G. A. 1987, ApJ, 322, L59
Songaila, A., & Cowie, L. L. 1996, AJ, 112, 335
Songaila, A., Hu, E. M., & Cowie, L. L. 1995, Nature, 375, 124
Tegmark, M., Silk, J., & Evrard, A. 1993, ApJ, 417, 54
On the enrichment of the intergalactic medium by galactic winds

Tegmark, M., Silk, J., Rees, M. J., Blanchard, A., Abel, T., & Palla, F. 1997, ApJ, 474, 1
Thoul, A. A., & Weinberg, D. H. 1995, ApJ, 442, 480
Trentham, N. 1994, Nature, 372, 157
Truran, J. W. 1981, A&A, 97, 391
Tytler, D. 1987, ApJ, 321, 49
Tytler, D., Fan, X.-M., Burles, S., Cottrell, L., Davis, C., Kirkman, D., & Zuo, L. 1995, in QSO Absorption Lines, ed. G. Meylan (Berlin: Springer-Verlag), p. 289
van den Bergh, S. 1992, A&A, 264, 75
Voinovich, P. A. & Chernin, A. D. 1995, Astronomy Lett., 21, 835 (translated from Pis’ma Astron. Zh. 1995, 21, 926)
Voit, G. M. 1996, ApJ, 465, 548
White, S. D. M., & Frenk, C. 1991, ApJ, 379, 52
Womble, D. S, Sargent, W. L. W., & Lyons, R. S. 1996, in Cold gas at High Redshift, eds. M. Bremer, H. Rottgering, P. van der Werf, C. Carilli (Kluwer), in press
Woosley, S. E., & Weaver, T. A. 1982, in Supernovae: A survey of current research, eds. M. J. Rees, R. J. Stoneham (Dordrecht: Reidel), p. 79
Yoshii, Y. 1981, A&A, 97, 280
Yoshii, Y., & Arimoto, N. 1987, A&A, 188, 13
Yoshioka, S. & Ikeuchi, S. 1990, ApJ, 360, 352