Semi–Analytic Simulations of Galactic Winds: Volume Filling Factor, Ejection of Metals and Parameter Study

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ewtextbf{ABSTRACT}
We present a semi–analytic treatment of galactic winds within high resolution, large scale cosmological N–body simulations of a ΛCDM Universe. The evolution of winds is investigated by following the expansion of supernova driven supershells around the several hundred thousand galaxies that form in an approximately spherical region of space with diameter 52h\textsuperscript{−1} Mpc and mean density close to the mean density of the Universe. We focus our attention on the impact of winds on the diffuse intergalactic medium. Initial conditions for mass loss at the base of winds are taken from Shu, Mo & Mao (2003). Results are presented for the volume filling factor and the mass fraction of IGM in winds and their dependence on the model parameters is carefully investigated. We find that a high volume filling factor does not necessarily correspond to a high mass fraction in wind shells, implying that even very spatially extended galactic winds may not leave detectable imprints on the Ly\textsubscript{α} forest. Low mass galaxies play a major role in seeding the IGM with metals at high redshift in models where winds sweep up little gas from the IGM and supernova ejecta constitute most of the mass in shells. The formation of winds in low mass galaxies is instead suppressed in models in which the mass of IGM entrained in winds is significant. In these models, the IGM is enriched at later times by galaxies with large stellar masses.

\textbf{Key words:} cosmology: theory – intergalactic medium – galaxies: evolution – methods: numerical


ewtextbf{1 INTRODUCTION}
Powerful outflows from star–forming galaxies have been detected throughout the history of the universe (Heckman, Armus & Miley 1990, Heckman et al. 2000, Adelberger et al. 2003), providing, perhaps, the mechanism to transport metals from the interstellar medium (ISM) of galaxies to the low density intergalactic medium (IGM). This could at least partially explain the widespread level of chemical enrichment observed in the spectra of quasars (Cowie et al. 1995, Schaye et al. 2000, Ellison et al. 1999).

The energy necessary to power outflows on galactic scales is supplied by supernova explosions and winds from young massive stars in OB associations. Any episode of star formation may create a superbubble in the ISM and, if the rate of energy input is large enough, the superbubble can blow out of the ISM and thus create a wind. In local starbursts (Phillips 1993, Cecil, Bland-Hawthorn & Veilleux 2002, Walter, Weiss & Scoville 2002, Sugai, Davies & Ward 2003), winds have been observed to extend to at least 10 kpc from their host galaxies. Strickland & Stevens (2000) claim that winds can reach even larger distances, but are unobservable because of the low emissivity of the outflowing gas.

At present, it is difficult to predict which galaxies are responsible for seeding the IGM with metals or to establish the effects that supernova–driven blastwaves have on the galaxy formation process. While gravity does not influence the evolution of superbubbles in the ISM, it is crucial for determining the long term fate of winds. Since winds from dwarf galaxies form in shallower potential wells, they are the more likely to be able to disperse their metal content into the IGM. On the other hand, Strickland & Stevens (2000) suggest that most of the energy from winds resides in a hot ($T \sim 10^7$ K) low density component able to escape the galaxies even when the bulk of the outflowing mass is retained and Mac Low & Ferrara (1999) demonstrate that metals are easily accelerated to velocities larger than the escape velocity, implying that a galaxy can lose a high fraction of its metals even with a relatively low mass ejection effi-
ciency. Although winds may occur more frequently in dwarf galaxies, the metals ejected by massive galaxies may dominate the total budget. It is therefore not a trivial problem to assess which galaxies have been responsible for the pollution of the IGM and when the enrichment occurred.

Several groups have applied simple phenomenological prescriptions to simulations in order to investigate the effects of winds on the IGM and some important results have emerged. For example, Madau, Ferrara & Rees (1999) find that pregalactic outflows are an efficient mechanism for distributing the metals produced in stars over large cosmological volumes, prior to the reionisation epoch. Aguirre et al. (2001) argue that radiation pressure ejection or winds from relatively large galaxies at lower redshifts can account for the observed metallicity of the IGM and the intracluster medium. Theuns, Mo & Schaye (2001) demonstrate that feedback signatures from LBG may be found in the Lyα forest and Croft et al. (2002) confirm that cavities evacuated by winds in the outskirts of galaxies may produce a large effect on the Lyα forest. In contrast, Theuns et al. (2002c) find that winds have little effect on the statistics of H I absorption lines and produce C IV absorption lines in reasonable agreement with observations.

Following this work, the significance of galactic winds for the evolution of the IGM is still not fully established. Both hydrodynamic and semi-analytic simulations use phenomenological prescriptions for the physics of galactic winds and new parameters have to be introduced to account for the uncertainties that derive from a still incomplete observational picture. In particular, no well founded relation is available to link the properties of the ISM and the galaxy morphology to the structure and evolution of the outflows. Because of insufficient resolution and incomplete physics, numerical results often disagree with each other and the effects of winds on the Lyα forest remain controversial, leaving the way open for further studies.

In this paper, we present a new implementation of the physics of galactic winds within the semi-analytic galaxy formation model of Springel et al. (2001), and we apply it to a set of high resolution N-body simulations of structure formation in a ΛCDM universe (Stoehr 2003, Ciardi, Stoehr and White 2003). By using a high resolution resimulation of a spherical region of radius 26 $h^{-1}$ Mpc selected from a much larger simulation of structure formation, we investigate the long term evolution of winds and their effects on a typical region of the IGM. We solve the equation of motion proposed by Ostriker & McKee (1988) for a spherical astrophysical blastwave in the thin shell approximation and follow the evolution of winds after they blow out of galaxies and expand into the IGM. Our model is not able to resolve the internal structure of galaxies, and in particular of their ISM. Our phenomenological model for winds instead uses the initial conditions recently proposed by Shu, Mo & Mao (2003). These parameterise the mass loss and the initial velocity of winds as a function of the star formation rate of the galaxy. We find that the global effects of winds depend sensitively on the efficiency parameter $K$ introduced by our initial conditions, but not as much as on the other parameter required by our model, the entrainment fraction $\varepsilon$, that determines how much matter is swept up by winds during their expansion.

Here we follow the evolution of galactic winds throughout most of the history of the universe and we outline their impact on the IGM by estimating the fraction of the volume and mass of the IGM which they affect as a function of time and of our model parameters. In our scheme, models with a high volume filling factor generally imply a low fraction of mass in shells, indicating that most of the IGM mass may be unaffected by the passage of winds so that the probability to find wind signatures in the Lyα forest is low.

This paper is organised as follows: in Section 2 we present our set of high resolution N-body simulations and the semi-analytic prescriptions we adopt to model the physics of galactic winds; in Section 3 we describe briefly our main results for the winds and outline some of their global properties as a function of our model parameters; in Sections 4 and 5 we present the results for the volume filling factor and the fraction of mass in shells of winds and show their dependence on model parameters; finally, in Section 8 we draw our conclusions.

2 SIMULATING GALAXY FORMATION AND FEEDBACK PROCESSES

2.1 The N–body Simulations

In this section, we describe the set of high resolution N–body simulations we use. Later subsections present in detail the prescriptions we adopt for the physics of galactic winds and their implementation in the semi–analytic code of Springel et al. (2001). We assume a ΛCDM cosmology with matter density $\Omega_m = 0.3$, dark energy density $\Omega_\Lambda = 0.7$, Hubble constant $h = 0.7$, primordial spectral index $n = 1$ and normalisation $\sigma_8 = 0.9$.

A high resolution in mass is crucial to assess the effects of galactic winds and to determine the role of galaxies with different masses in polluting the IGM with metals. The use of pure N–body simulations allows us to find a good compromise between high mass resolution and a large simulated volume, although this choice implies that the physics of baryons cannot be followed directly. A large region is necessary to study the effects of winds in their proper cosmological context.

Our simulations are resimulations at higher resolution of a "typical" spherical region with a diameter of approximately 52 $h^{-1}$ Mpc and average density close to the cosmic mean. About half of the enclosed galaxies are field galaxies, while the rest are in groups and poor clusters. The simulated region was identified within the much larger cosmological "VLS" simulation run by the VIRGO Consortium (Jenkins et al. 2001, Yoshida, Sheth & Diaferio 2001). It was resimulated four times with increasing internal mass resolution and decreased external resolution. The effects of the large scale gravity field on the region of interest are correctly retained. The particle masses in the high resolution region are $M_p = 6.8 \times 10^{10} h^{-1} M_{\odot}$ for "M0", $4.8 \times 10^9 h^{-1} M_{\odot}$ for "M1", $9.5 \times 10^8 h^{-1} M_{\odot}$ for "M2" and $1.7 \times 10^8 h^{-1} M_{\odot}$ for "M3". The number of dark matter particles in the high resolution region in M3 is about $7 \times 10^7$. The initial conditions were generated with ZIC (Tormen, Bouchet & White 1997) and the simulations were performed using the parallel treecode GADGET (Springel, Yoshida & White 2001). The dark matter evolution is followed from redshift $z = 120$ down to redshift $z = 0$. 

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and 52 simulation outputs were stored between \( z = 20 \) and \( z = 0 \).

### 2.2 Galaxy Formation and Star Formation History

The formation and evolution of galaxies is modelled with the semi-analytic technique proposed by Kauffmann et al. (1999) in the new implementation by Springel et al. (2001). Merging trees extracted from the simulations are used to follow the galaxy population in time, while simple prescriptions for gas cooling, star formation and galaxy merging model the processes involving the baryonic component of the galaxies. The spectrophotometric evolution of the stellar population and the morphological evolution of galaxies can thus be recovered.

Dark matter haloes and subhaloes are identified with the algorithm SUBFIND (Springel et al. 2001) and a catalogue is compiled with all the groups and subhaloes that contain at least ten particles, meaning that for M3 the minimum dark matter mass of a subhalo is \( 1.7 \cdot 10^7 \text{M}_\odot \).

At \( z = 3 \) a total of about four hundred thousand galaxies are identified and about three hundred fifty thousand are present at \( z = 0 \). The two largest clusters, each with a total mass of about \( 10^{14} \text{h}^{-1} \text{M}_\odot \), assemble most of their mass after \( z \sim 1 \).

The convergence of the star formation history in the "M" series of simulations has recently been investigated by Ciardi, Stoehr and White (2003). They show that the lower the galaxy mass, the later in time the simulations are able to account for all the star formation in the region, since at redshifts higher than \( z \sim 10 \) the major contribution comes from objects with total masses of order \( 10^9 \text{M}_\odot \), while only at lower redshifts do more massive objects appear and become dominant. By comparing the results of the star formation history of M3 with a higher resolution cluster simulation by Springel et al. (2001), Ciardi and collaborators estimate that M3 is able to account for most of the star formation at \( z \lesssim 11 \).

### 2.3 Feedback Prescriptions

In this paper, new recipes for mechanical feedback from supernovae are introduced in order to include the physics of galactic winds.

Kauffmann et al. (1999) and Springel et al. (2001) find that a simple recipe for feedback from supernovae, implemented in the so-called "ejection" scheme, is sufficient to give accurate predictions for some observed properties of galaxies, e.g. the suppression of star formation in low mass haloes and the slope of the Tully–Fisher relation. The simplicity of this prescription makes it impossible however to follow in detail the evolution of galactic winds. In particular, the scheme does not describe the diffusion of the matter and metals lost by galaxies, because there are no recipes for following the evolution of shells and wind ejecta. This is what we aim to provide in this paper.

Here we use the semi-analytic model of Springel et al. (2001) with the implementation of the ejection scheme, without modifying its prescriptions, to follow the evolution of the cold gas and the stellar component of the galaxies. We add our recipes for winds on top of this pre-existing scheme. This is not fully consistent, because we do not modify the cooling and the infall prescriptions in the semi-analytic code to match our new model for the immediate surroundings of our galaxies. One consequence of this is that the total metal and gas mass in our simulated region is not exactly conserved. However, violations are minor.

Since we want to investigate the effects of winds on the IGM by applying our model to a large simulated region, we are neither able nor interested to resolve the details of the first phases of wind evolution, when the superbubbles blow out of the ISM of galaxies. Nor do we model in detail the impact of the outflow on the physical conditions of the ISM in the host galaxy. Here, we are concerned with the long-term evolution of the winds once they have escaped the visible regions of galaxies.

We make the simplifying assumption of spherical symmetry for the wind evolution. Galactic outflows observed in nearby galaxies appear to be mostly bipolar (Heckman et al. 2000), with the gas escaping preferentially along the direction where the gravitational potential gradient is stronger. However, observations of high redshift objects (Frye, Broadhurst & Benitez 2002, Pettini et al. 2002) suggest that most galaxies are affected by large scale winds implying near spherical outflows. Together with the fact that an initially nonspherical shell approaches sphericity at later times (Ostriker & McKee 1988), this suggests that our symmetry assumption may be appropriate.

The thermal energy injected by supernova explosions is converted to kinetic energy and the outflow remains approximately adiabatic until radiative losses become substantial. Hoopes et al. (2003) and Strickland & Stevens (2000) have recently proved that the energy lost through radiative cooling of the coronal \((T \sim 10^{5.5} \text{K})\) and the hot \((T \sim 10^7 \text{K})\) phases of the wind in the starburst galaxy M82 is small. The wind can be thus described as a cosmological blastwave expanding in the galactic halo or in the IGM, whose dynamics obeys the virial theorem for blastwaves as stated by Ostriker & McKee (1988).

In the thin shell approximation all the gas accumulates in a shell of zero thickness with the radius and velocity of the shell equal to the radius and velocity of the shock. Although for adiabatic blastwaves in an homogeneous medium the thin shell approximation is valid only in the case of a soft equation of state, for cosmological blastwaves it is always valid, since the gas piles up just behind the shock front because of the expansion of the universe. In this approximation, the equation of motion of a spherical shell with energy injection at the origin results from the conservation of momentum,

\[
\frac{d}{dt}(mv) = \dot{M}_w (v_w - v) - \frac{GM_{\text{igm}} m}{r^2} - 4\pi r^2 \gamma \rho_{\text{igm}} c^2 v_w - \varepsilon 4\pi r^2 \rho_{\text{igm}} v_{\text{igm}} (v + v_{\text{igm}}),
\]

where \( m, r \) and \( v \) are the mass, the radius and the outflow velocity of the shell, \( \dot{M}_w \) and \( v_w \) the mass outflow rate and the outflow velocity of the wind, \( \rho_{\text{igm}} \) and \( v_{\text{igm}} \) the density and the infall velocity of the surrounding medium, \( M_0 \) the total mass internal to the shell, \( \gamma \) the adiabatic index and \( \varepsilon \) a parameter, the entrainment fraction, defining the fraction of mass that the shell sweeps up while crossing the ambient medium. The first term on the right-hand side of the equation represents the momentum injected by supernovae, the
second term takes into account the gravitational attraction of the dark matter halo and the two final terms represent the thermal and the ram pressure of the surrounding medium. The conservation of mass gives

\[
\frac{dm}{dt} = M_w \left( 1 - \frac{v}{v_w} \right) + \varepsilon \pi r^2 \rho_{igm} (v + v_{igm}). \tag{2}
\]

The mass accumulated in the shell is the sum of the wind mass that reaches the shock and the swept-up mass. The radius of the shell is given by \( v = dr/dt \).

At blow out, that is when the wind escapes the galactic disk or spheroid, we assume that a shell is formed initially with no mass \( m(r_o) = 0 \), a radius equal to the galaxy radius \( r_g \) \( (r_o = r_g) \) and zero velocity \( (v(r_o) = 0) \). After blow out, the shell starts to accumulate gas. Since our semi-analytic model does not follow the internal structure of galaxies, we have to make a further assumption for the galaxy radius, in order to link it to the properties of the dark matter halo in which the galaxy is embedded. Thus we fix \( r_g \) to be a given fraction of the virial radius of the DM halo, e.g. \( r_g = r_{200}/10 \). This choice gives values in rough agreement with the observed radii of galaxies at all redshifts.

The equations above have previously been used in similar work by Theuns, Mo & Schaye (2001) and Aguirre et al. (2001), but with some noteworthy differences in the initialisation of the shell properties. For instance, Theuns, Mo & Schaye (2001) fix the initial conditions at the virial radius and assume that the shell velocity equals the wind velocity, while the mass is equal to \( m = (\Omega_b/\Omega_m) M_{vir} \). This choice is quite surprising, since it implies that they blow out all the baryonic mass of the galaxy, including stars. Aguirre et al. (2001) set initial conditions for \( m, r \) and \( v \) by choosing a radius \( r_o \) to include a fixed fraction \( \xi \) of the galaxy mass and the constant \( \xi \) is calibrated to give values of \( r_o \) similar to the radii at which winds from starbursts are observed. The resulting shell mass is therefore \( m(r_o) \propto \xi M_{gal} \), but it is not clear what fraction of the galaxy mass is already entrained in the outflow when the shell emerges from the galaxy.

\[\text{2.3.1 Wind Velocity and Mass Loss Rate}\]

At present, both semi-analytic and SPH simulations use empirical prescriptions for the physics of galactic winds and the velocity and the mass outflow rate are assumed as parameters (e.g. Springel & Hernquist 2003, Aguirre et al. 2001, Theuns et al. 2002c, Thacker, Scannapieco & Davis 2002). This approach has proved useful, although the simulated results depend sensitively and in a complex fashion on the choice of the parameters.

Shu, Mo & Mao (2003) recently proposed a more detailed model that links the winds and the star formation properties of galaxies. They start from two observational facts: (i) the outflow rate in galaxies at every redshift is of the order of the star formation rate (Martin 1999) and (ii) the initial wind velocities seem to be independent of the galaxy morphologies (Heckman et al. 2000, Frye, Broadhurst & Benitez 2002) and lie in the range 100–1500 km s\(^{-1}\). By using the theoretical models of McKee & Ostriker (1977) and Efstathiou (2000), they predict the mass outflow rate \( M_w \) and the wind velocity \( v_w \) at blow out as a function of the star formation rate \( M_\star \) of the host galaxy,

\[
M_w = 133 \left( \frac{M_\star}{100M_\odot \text{ yr}^{-1}} \right)^{0.71} K M_\odot \text{ yr}^{-1}, \tag{3}
\]

\[
v_w = 623 \left( \frac{M_\star}{100M_\odot \text{ yr}^{-1}} \right)^{0.145} K^{-1/2} \text{ km s}^{-1}, \tag{4}
\]

where \( K \) is a constant that takes into account various properties of the ISM. It depends on the efficiency of conduction relative to the thermal conductivity of clouds, on the minimum radius of clouds in the ISM and on the dimensions of star-forming regions (see Shu, Mo & Mao 2003 for a comprehensive discussion). In the following, we will call the ratio between the wind mass loss rate and the star formation rate the “reheating efficiency” \( R_{eff} = M_w/M_\star \) of the wind.

Note that the momentum input \( \dot{M}_w v_w \) in this model is only weakly dependent on \( K (\propto K^{1/2}) \), with a stronger dependence on the star formation rate \( (\propto M_\star^{0.855}) \). The energy input is proportional to the star formation rate, but is completely independent of \( K \) and therefore of all other galaxy properties. Shu, Mo & Mao (2003) give a number of arguments in support of this very simple model which is quite similar to the earlier model of Dekel & Silk (1986). With their assumptions, galaxies with more compact star-forming regions produce winds with higher velocities and lower outflow rates and vice versa.

The theoretical predictions can be fine-tuned to reproduce the observations with reasonable accuracy both for the mass loss rate and the wind velocity. We choose as our fiducial value \( K = 0.5 \). In order to make our predictions consistent with the observations of Martin (1999), we fix a maximum value for the reheating efficiency of \( R_{eff} \leq 5 \). Equations 3 and 4 tend to overestimate \( R_{eff} \) for low values of the star formation rate.

We will show in the following sections that the numerical results of our simulations do depend on the precise value of \( K \). The major dependence however is on the other parameter in the model, the entrainment fraction \( \varepsilon \). For convenience, in the following we will refer to the model with \( K = 0.5 \) and \( \varepsilon = 0.1 \) as our fiducial model.

\[\text{2.3.2 Metals in Shells}\]

The mass ejected by winds is the sum of two components: the metal enriched stellar ejecta from supernova explosions and the shocked, heated and accelerated ISM entrained in the outflow. The latter represents the major fraction of the mass lost by the galaxy, constituting more than 90% of the ejecta, since the mass loss rate is comparable to the star formation rate in the galaxy driving the wind. Assuming for star formation a yield \( Y = 0.02 \), corresponding to the fraction of mass converted into stars that is returned to the ISM by supernova explosions in the form of metals, then the mass of outflowing gas which is entrained ISM is \( \Delta M_s (R_{eff} - Y) \). The metallicity of the wind fluid depends both on the amount of metals ejected by supernovae and on the metallicity of the ISM.

In our semi-analytic model, galaxies are schematically represented as a disc of cold gas, which constitutes the ISM of the galaxy, surrounded by a halo of hot gas. As for the total mass ejected by winds, the mass of metals entrained
in the wind fluid and deposited in shells is the sum of two contributions: the metals in the supernova ejecta and the metals in the ISM blown out of the host galaxy

\[ M_{z,w} = \dot{M}_w dt \left( Y + (R_{eff} - Y) Z_{cold} \right), \]

where \( Z_{cold} \) is the metallicity of the cold gas. The total mass of metals accreted by a shell reflects the form of the mass conservation equation (2) and is the sum of the metals accreted from the wind fluid and the metals accreted from the ambient medium:

\[
\Delta m_z = \Delta m_{z,w} + \Delta m_{z,e} = \dot{M}_w \Delta t \left( Y + (R_{eff} - Y) Z_{cold} \right) \left( 1 - \frac{v}{v_w} \right) + \\
+ \varepsilon 4\pi r^2 \rho (v + v_{igm}) Z_{hot} \Delta t. \tag{6}
\]

with \( Z_{hot} \) the metallicity of the hot gas. The second term indicates the amount of metals swept up by the shell in the halo of the galaxy and does not give any contribution for shells that are expanding far into the IGM, since the IGM itself is assumed to contain no metals until it is traversed by an ejected shell.

2.3.3 The Wind Environment

Once a shell is formed, it expands through the halo of its host galaxy and, if it is energetic enough, it can escape the gravitational attraction of the halo and break out into the IGM. Our simulations contain no rich clusters and about half of the galaxies at \( z = 0 \) belong to groups or small clusters. The shells attached to these galaxies are subject to the gravitational field of the group and the closer a galaxy lies to the centre of a massive group, the more energetic the wind has to be to be able to escape the potential well of its host.

When simulating the evolution of the winds, it is therefore important to know the density distribution of the gas into which the shells expand. Our semi-analytic prescriptions provide this information by assuming that inside dark matter haloes the gas follows the distribution of the dark matter.

We model the gravitational fields of haloes and their gas distribution by using Navarro, Frenk & White (1996) profiles

\[
\rho_{NFW}(r) = \frac{\delta \rho_c(z)}{\left( r \over r_s \right)^2 \left( 1 + r \over r_s \right)^2}, \tag{7}
\]

where the characteristic overdensity \( \delta \) is given by:

\[
\delta = \frac{200}{3} \frac{c^3}{F(c)}, \tag{8}
\]

and where we choose the concentration parameter \( c = 10 \) as our fiducial value. The scale radius \( r_s \) is the ratio \( r_s = r_{200} / c \) and the function \( F(t) \) is given by:

\[
F(t) = \log(1 + t) - \frac{t}{1 + t}. \tag{9}
\]

Inside haloes, the gas density is normalised to the total amount of hot gas given by the semi-analytic recipes of Springel et al. (2001), that is \( \rho_{igm} = (M_{hot}/M_{200}) \rho_{NFW} \). For galaxies in groups or clusters, we follow the density profile of the galactic halo until its density equals the density of the parent halo, where the dynamics of the group becomes dominant. Similarly, the density profile of the group is followed until the shell reaches the point where the dark matter halo density becomes equal to a fixed fraction of the mean universal density. After this point, the gas density is assumed to be constant and equal to 0.8 times the baryonic mean density.

The velocity of the surrounding medium \( v_{igm} \) is calculated assuming that the gas dynamics is dominated by infall close to galaxies and by the Hubble flow at larger distances. The inward \( v_{igm} \) is therefore given by the sum of two contributions:

\[
v_{igm} = v_{esc} - H(z) \cdot r. \tag{10}
\]

The escape velocity \( v_{esc} \) at a radius \( r \) for a NFW profile is

\[
v_{esc}^2(r) = \frac{2GM_{200} \log(1 + r / r_c)}{r F(c)} . \tag{11}
\]

When the velocity of the shell equals the velocity of the gas, the shell joins the Hubble flow and no more mass is accreted.

The entrainment fraction \( \varepsilon \) represents the fraction of the ambient gas that is swept up by the shell and is treated as a free parameter. The remaining fraction of mass \( 1 - \varepsilon \) is assumed to be in dense clouds which are unperturbed by the shell. A low value \( \varepsilon \ll 1 \) may reflect either a clumpy ambient medium or a heavily fragmented shell, while \( \varepsilon \sim 1 \) describes a near–homogeneous medium, which can be entirely swept up by the wind.

This parameter is of particular relevance because it plays a key role in determining the fate of the wind: the mass accretion rate of the shell depends on \( \varepsilon \) and the more massive the shell, the bigger the energy required to accelerate it. In addition, the ram pressure increases linearly with \( \varepsilon \), influencing directly the energetics of the winds. The net effect of an increase in the entrainment fraction is thus a decrease in the shell speed, which may lead to the recollapse of the shell if the energy input from the starburst is not sufficiently large. Since the velocity of the shells is what ultimately determines how far into the IGM the winds travel, a large variation of the volume filling factor of winds is expected as \( \varepsilon \) varies. We will analyze this aspect further in section 4.

2.3.4 Shell Merging

When two galaxies merge, we assume that also their shells “merge”. If only one galaxy is blowing a wind, then its shell will be attached to the merged galaxy without modifications. The merging of shells is realised by assuming conservation of volume, mass and momentum of the shells.

Conservation of mass requires the final mass \( m \) of the new shell to be the sum of the masses \( m_1 \) and \( m_2 \) of the two merging shells, that is \( m = m_1 + m_2 \). Similarly, the metal mass in the merged shell is \( m_z = m_{1,z} + m_{2,z} \).

Conservation of volume requires that the total volume \( V \) of the final shell is equal to the sum of the volumes of the two single shells \( V = V_1 + V_2 \). Since shells are spherical, the radius of the new shell is \( r = (r_1^3 + r_2^3)^{1/3} \).
The velocity of the resulting shell is given by the conservation of momentum:

\[ v = \frac{m_1v_1 + m_2v_2}{m_1 + m_2}. \] (12)

3 EVOLUTION OF WINDS

In this section we will discuss the evolution of winds and how our results depend on our model assumptions and parameters. In particular, we will show in paragraph 3.1 the evolution of a wind, chosen randomly from the galaxy population. In paragraph 3.2 we focus on the population of wind cavities and shells.

3.1 Single Galaxy

As already stated, the entrainment fraction \( \varepsilon \) determines what fraction of the medium that a shell crosses is swept up and joins the shell itself. New-born winds expand initially inside the dark matter halo of their host galaxies. Since the total amount of gas in haloes depends on the efficiency of cooling and may vary significantly from galaxy to galaxy, each galaxy has a "personal" history different from all the others.

In Fig. 1 we show the evolution in time of a shell emerging from a galaxy, chosen randomly from the galaxy population of M3, as a function of our model parameters \( K \) and \( \varepsilon \). The galaxy is initially a central galaxy, but after \( z = 1 \) it falls into a larger group and becomes a satellite. Different lines show results for different parameter choices. The thick solid line shows our fiducial model. In the mid–right panel we show the star formation history of the galaxy, which forms stars in a rather continuous way throughout its lifetime: at low redshift the star formation rate is very low, but it never goes to zero.

This galaxy gives a good example of several features that may appear during the life of galaxies and winds. For example, the vertical jump at \( z \sim 2 \) in the bottom right panel is due to the merging of a large satellite onto the galaxy, which triggers a burst of star formation. The merging of the two wind shells is instead responsible for the jumps observed in the left panels of Fig. 1. Again in the left panels of Fig. 1, in some of the models the shells stop accreting mass, while the radius and the velocity increase slowly. This is because the shell has escaped the attraction of the galaxy and has finally joined the Hubble flow.

As a general trend, we observe that more massive shells tend to be slower and to collapse more easily than lighter ones. The initial conditions set by equations 3 and 4 imply that the mass loss rate is inversely proportional to the velocity of the wind. Although the total momentum input is almost the same, the gravitational attraction felt by the shell increases significantly and the combined effect is a low velocity for the shell, often much smaller than the escape velocity from the galaxy as given by equation 11. Even when massive shells are able to escape into the IGM, the distances they can travel are much smaller than those of light shells.

While changes in the parameter \( K \) only weakly affect the long term evolution of the winds, the entrainment fraction \( \varepsilon \) plays a crucial role, because it determines directly the mass accretion rate and therefore the momentum loss by ram pressure and gravity effects. A very low entrainment fraction creates an extremely light shell that can travel far into the IGM with a relatively high speed, while if \( \varepsilon \sim 1 \) the shell sweeps up all the mass it encounters and becomes more and more massive, a condition that increases the probability of collapse. Since the mass swept up by shells in the IGM is assumed to have zero metallicity, the metal abundance in the shells increases with decreasing \( \varepsilon \). We will show in the next sections how a high entrainment fraction can reduce drastically the filling factors of winds.

3.2 Properties of the Shell Population

In this paragraph we will outline how varying the parameters \( \varepsilon \) and \( K \) affects the global properties of the winds, focusing our attention in particular on the mass and the radius of the shells.

Since the total number of galaxies in M3 is very large, we calculate various "mean" quantities to describe the global properties of the winds, and do not focus further on individual cases. We would like to point out that this necessarily gives a partial idea of the whole picture, since there are no strong correlations between the properties of the galaxies and those of the winds. It is likely that if a massive galaxy is blowing a wind, then that wind started before most of the halo mass was accreted and the shell was expelled to a large radius at early times. Winds from massive galaxies can also

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reach large distances in relatively short times if the burst of star formation that powers them is strong enough. Furthermore, there is no clear connection between the present star formation rate of a galaxy and the properties of the wind. The star formation activity of a galaxy may switch off or decrease to very low values, while the wind still has sufficient energy to escape the gravitational pull without further energy input. It is common in our simulations to find winds expanding in the IGM a considerable time after the star formation activity and the momentum input from the source galaxy have ceased.

Both bursts of star formation and quiescent star formation activity are able to power the winds and drive them far into the IGM. It is not obvious a priori when a wind will escape the gravitational pull of a galaxy. A shell that is collapsing onto a galaxy may receive new energy from increased star formation activity, triggered by mergers or gas accretion, for example, and it may start expanding again. On the other hand, an expanding shell may start to recollapse because its host galaxy merges and the gravitational attraction increases by a large factor.

The evolution and the final fate of winds are linked to several factors, like the star formation and the mass accretion history of the galaxy, the potential well of the dark
The mean shell radius (top panel) and the mean shell mass (bottom panel) for all the galaxies blowing a wind at $z=3$, as a function of the stellar mass $M_\star$ of the host galaxy. The data are shown for different combinations of the model parameters (these same notations will be maintained throughout all the paper for the model parameters): (1) thick solid line (fiducial model): $K = 0.5$, $\epsilon = 0.1$; (2) dotted line: $K = 0.1$, $\epsilon = 0.1$; (3) dashed line: $K = 1$, $\epsilon = 0.1$; (4) dashed dotted line: $K = 0.5$, $\epsilon = 1$; (5) dashed three-dotted line: $K = 0.5$, $\epsilon = 0.01$; (6) long dashed line: $K = 0.1$, $\epsilon = 0.01$; (7) thin solid line: $K = 1$, $\epsilon = 1$.

Figure 3. The mean shell radius (top panel) and the mean shell mass (bottom panel) for all the galaxies blowing a wind at $z=3$, as a function of the stellar mass $M_\star$ of the host galaxy. The data are shown for different combinations of the model parameters (these same notations will be maintained throughout all the paper for the model parameters): (1) thick solid line (fiducial model): $K = 0.5$, $\epsilon = 0.1$; (2) dotted line: $K = 0.1$, $\epsilon = 0.1$; (3) dashed line: $K = 1$, $\epsilon = 0.1$; (4) dashed dotted line: $K = 0.5$, $\epsilon = 1$; (5) dashed three-dotted line: $K = 0.5$, $\epsilon = 0.01$; (6) long dashed line: $K = 0.1$, $\epsilon = 0.01$; (7) thin solid line: $K = 1$, $\epsilon = 1$.

Keeping all this in mind, in Fig. 2 we consider only those galaxies which are blowing a wind and we plot the mean values of the radii and the shell masses of all the winds as a function of the stellar mass $M_\star$ for different epochs of our fiducial model. The data have been binned according to intervals of $M_\star$ of variable extension and the mean values have been calculated for each group. Clearly, the mean radius and the mean mass increase with time, as the winds have more time to expand further from the galaxies. For galaxies of larger masses the mean radius appears to be considerably larger than for less massive ones. This effect has two explanations: first, these winds need higher velocities to be able to escape from the gravitational attraction of their haloes and therefore can cover larger distances; secondly, they often started earlier in time.

In Fig. 3 we plot the same quantities, but for different choices of the model parameters at $z=3$. The scatter in the plot is large and the results differ from our fiducial model by as much as a factor of five in the most extreme cases. Once again, this is due to the scatter in the initial velocities and the accretion of mass onto the shells, as already noted in the case of a single galaxy in Fig. 1. The most massive shells tend to travel to shorter distances than the lighter ones, their mass being determined both by the fraction of entrained gas from the IGM (determined by $\epsilon$) and/or the mass injected by the wind (linked to the parameter $K$).

In Fig. 4 we show the fraction of galaxies with $M_\star > 10^8 M_\odot$ blowing a wind as a function of redshift. In Fig. 5 we show the fraction of galaxies with winds as a function of stellar mass at $z=3$. Both quantities are plotted for different parameter choices. The number of galaxies blowing a wind depends strongly on the model parameters. In particular, the entrainment fraction greatly affects the ability of galaxies with low stellar masses, which dominate the stellar counts, to power a wind. A large amount of mass in a shell requires a larger rate of energy injection from the galaxy for

Figure 4. The fraction of wind–blowing galaxies as a function of redshift and model parameters. Here we consider only galaxies with $M_\star > 10^8 M_\odot$. A large amount of swept up mass from the surrounding medium strongly suppresses the ability of galaxies to power outflows. The lines correspond to different parameter choices as in Fig. 3.

Figure 5. The differential fraction of wind–blowing galaxies at $z=3$ as a function of stellar mass. The lines correspond to different parameter choices as in Fig. 3.
the shell to escape. When this does not happen, the shell collapses back onto the galaxy. The overall effect is to reduce the number of wind–blowing galaxies by a large factor. A similar but much weaker effect is produced by the parameter $K$.

Why can winds with a very low entrainment fraction escape galaxies so much more efficiently than more mass loaded ones? Why is this effect particularly strong in low stellar mass galaxies? Let’s consider equation (1) for the conservation of momentum. A shell receives energy from the wind and is slowed down by the gravitational attraction of the central galaxy and by the ram pressure of the ambient medium. Thermal pressure effects are generally negligible. If the mass entrained by a wind is small, as in the case of $\varepsilon = 0.01$, then the shell mass is roughly comparable to the mass of supernova ejecta that reaches the shell. These are outflowing from the galaxy with a velocity which is often much larger than the escape velocity of the galaxy. Since little energy has to be spent by the wind to accelerate the entrained IGM, the velocity of the shell is less sensitive to energy losses by ram pressure and gravity. Such a wind thus has a higher probability to overcome the gravitational pull and break free from the halo than more mass loaded winds. When the mass loading is substantial, a significant part of the wind energy is consumed to accelerate the entrained gas and the shell slows down. If the amount of energy spent to accelerate the swept up IGM is large, the velocity of the shell may become lower than the escape velocity of the galaxy. In this case, the shell cannot escape and recollapses onto the galaxy. The mass loading of a shell immediately after blow out is therefore crucial to determine the fate of a wind.

In models with efficient mass loading, the suppression of winds is particularly strong in galaxies with low stellar masses. This is because the delicate momentum balance at blow out is easily dominated by momentum losses by ram pressure, which sum up to the ones by gravity. To make the situation worse, the energy input in low mass galaxies is often not as large as in more massive ones, due to a less intense star formation activity.

4 VOLUME FILLING FACTOR OF WINDS

An estimate of the volume filling factor $f_v$ of galactic winds at the redshifts where absorption in quasar spectra is observed can be translated into an estimate of the probability to find disturbances in the Lyα forest due to feedback effects and, in particular, to the presence of wind cavities and shells. Disturbances here mean regions of the spectra where there are significant variations in the optical depth, due to nongravitational processes stirring the IGM.

Observationally, it is quite challenging to estimate $f_v$ with any accuracy. Published estimates range from 0.003 to 40% (Heckman et al. 2001, Cecil et al. 2001, Rauch 2002) at $z \sim 3$. Surely the large scatter is due to the fact that the estimates are mostly indirect and are based on different, perhaps incompatible, assumptions, for example, about the geometry of the disturbances.

In Fig. 6 we show an example of the evolution of winds from $z = 5$ to $z = 0$. A thin slice is cut through the central plane of the simulation and the density distribution of the gas in the slice is shown. The contours indicate the surface of the wind shells and the black regions inside these contours represent the regions which have been depleted of low density gas by winds. To obtain these simulated distributions, we proceeded as follows. First we recover the density of the gas by applying an SPH smoothing to the distribution of the dark matter particles and by assuming that the distribution of the gas follows the distribution of the dark matter. We then identify the portion of space which is inside one or more shells and we consider only those particles that are found inside this region. Particles outside this region are of course not affected by winds. We compute the fraction $x$ of baryons removed from the IGM as the ratio of the total baryon mass of the shells plus the galaxies to the total baryonic mass initially associated with the dark matter inside shells. We then tag the lowest density particles in the region affected by winds until the same fraction $x$ of the enclosed mass is marked. Finally, we cut a thin slice through the density distribution of the remaining particles in our simulated region, as represented in Fig. 6. The amount of mass in shells varies strongly as a function of the entrainment fraction.

We calculate the filling factor of winds by superimposing a 3-dimensional grid on our high resolution region and identifying all the grid points inside winds. Since $f_v$ represents the fraction of space occupied by winds, its value is given simply by the ratio between the number of points flagged and the total number of points in the grid. Note that this estimate ignores the mass fraction $1 - \varepsilon$ of the IGM which is in “dense clouds” and so avoided entrainment.

We start drawing a $N \times N \times N$ cubic grid, centered on the centre of mass of the high resolution region and with a side of 52 $h^{-1}$ Mpc. For simplicity, we limit our analysis to a sphere of diameter 52 $h^{-1}$ Mpc, but a larger region with irregular contours could be identified. We include in our calculations only grid points in the interior of the sphere. In our analysis, we always use $N = 512$.

Our model parameters affects strongly the long term evolution of winds. In particular, the distance to which a shell can travel depends crucially on the total amount of mass accreted by the shell and therefore on the fraction of the IGM mass entrained in the outflow as set by $\varepsilon$. The general trend highlighted in paragraph 3.1 for a single wind is
recovered also for the behaviour of the volume filling factor. Once again, the smaller values for $f_v$ are related to the cases where more massive shells are formed and expand into the IGM with relatively low velocities.

In Fig. 7 the volume filling factor is shown as a function of time and of the two model parameters. By varying $K$ and $\varepsilon$ we are able to obtain a very broad range of values of $f_v$ at every redshift.

After $z \sim 2$ the fraction of volume occupied by winds still increases steadily, but, taking into account the conversion between redshift and cosmic time, less strongly than before. This is probably due to the clustering of the wind sources, which becomes more prominent at lower $z$. As the galaxies cluster, the probability that two shells overlap increases. We do not model the overlapping of shells in a complete way, since our one-dimensional approach does not allow us to take into account the three-dimensional distribution of galaxies and shells on the sky, but we can quantify a posteriori the overlapping of wind bubbles. In the following, we define $f_o$ as the fraction of our simulated volume which is reached by more than one wind. This definition is analogous to the definition of $f_v$, and in practice $f_o$ can be evaluated.
simply by counting the fraction of grid points that lie in two or more spherical wind bubbles.

In Fig. 8 we show the results of such a measurement for our fiducial model. Because the galaxies are associated in groups, the wind cavities occupy a smaller fraction of space than they would if they were randomly distributed. At the same time, shells can run into each other much more easily, than they would if they were randomly distributed. At the groups, the wind cavities occupy a smaller fraction of space in our fiducial model. Because the galaxies are associated in distributed sources (dashed line).

In the cases of clustered sources (solid line) and randomly distributed in our simulated region. Both cases have been realised for our fiducial model with \( K = 0.5 \) and \( \varepsilon = 0.1 \). The lines represent respectively: (1) thick solid line: fiducial model; (2) dotted line: overlapping for the fiducial model; (3) dashed line: random positions; (4) dashed dotted line: overlapping for the random positions model. In the bottom panel we compare the ratio \( f_o/f_v \) in the cases of clustered sources (solid line) and randomly distributed sources (dashed line).

The top panel shows the volume filling factor of winds \( f_v \) and the overlapping of shells \( f_o \) for M3 in the case of clustered sources and in the case that the sources were randomly distributed in our simulated region. Both cases have been realised for our fiducial model with \( K = 0.5 \) and \( \varepsilon = 0.1 \). The lines represent respectively: (1) thick solid line: fiducial model; (2) dotted line: overlapping for the fiducial model; (3) dashed line: random positions; (4) dashed dotted line: overlapping for the random positions model. In the bottom panel we compare the ratio \( f_o/f_v \) in the cases of clustered sources (solid line) and randomly distributed sources (dashed line).

The shell mass fraction is lower than 10% for every model at \( z \sim 10 \). The fact that \( f_o/f_v \) at \( z \sim 0 \) for clustered galaxies is smaller than for Poisson distributed ones is a result of overlapping of multiple winds in the same region.

Note that we are here dealing with a “field” region. We would expect the ratio \( f_o/f_v \) to behave differently in a region with more groups or clusters. There would be even more overlapping of winds, if the shells could expand as far as they do for field galaxies.

5 THE WIND MASS BUDGET

A second important indicator of the impact of winds on the surrounding medium is the fraction of intergalactic gas that they affect. This “shell mass fraction” \( f_m \), hereafter) is directly dependent on the entrainment fraction and on the mass of gas ejected by the galaxies. We estimate \( f_m \) as the ratio of the mass in shells to the total mass of IGM in our simulated box. We show our results in Fig. 9.

While \( f_v \) is determined only by the physical extension of shells, \( f_m \) is somewhat more difficult to estimate. In fact, one has to deal correctly with the overlapping of bubbles, which is not treated self–consistently in our semi–analytic prescriptions. To do this, we have to correct approximately for the fact that in our spherical wind model the same material can effectively be swept up two or more times when wind bubbles overlap. We first calculate the total mass of IGM inside shells in two different ways, that is from the dark matter particle distribution \( (m_{igm,p}) \) and from our semi–analytic prescriptions for the distribution of gas around galaxies, given in subparagrap 2.3.3. \( (m_{igm,sa}) \). The first method reflects the “real” 3–dimensional distribution of matter in our simulated region. We then define \( y \) as the ratio between the two, that is \( y = m_{igm,p}/m_{igm,sa} \). The shell mass, defined in equation 2, is the sum of the mass from supernova ejecta and of the gas mass entrained along the way: \( m = m_w + m_e \). The mass of supernova ejecta \( m_w \) is independent of overlapping effects. Conversely, the entrained mass \( m_e \) depends on overlapping and we thus rescale it by the factor \( y \) to obtain the actual swept up mass \( m'_e = ym_e \). The rescaled shell mass is thus \( m' = m_w + m'_e \). Finally, we calculate the fraction of IGM mass in shells as \( f_m = m'/m_{igm,p} \).

The shell mass fraction \( f_m \) varies differently from the volume filling factor \( f_v \) of winds. By comparing Fig. 9 and 7, it is immediately clear that, particularly at low redshifts, winds with low entrainment fraction have in most cases the largest \( f_v \) and the smallest \( f_m \), and viceversa. \( f_m \) is often lower than the volume filling factor, indicating that although shells can travel far into the IGM, the effective amount of mass affected is small. Consistently with this, the models with the highest values of \( f_m \) at \( z = 0 \) are those with \( \varepsilon = 1 \). The shell mass fraction is lower than 10% for every model.
at $z > 3$, and at $z \lesssim 2$ is still lower than 20%. The volume filling factor can already reach much higher values at these redshifts.

Although our model of partial entrainment does not address the detailed physics of shells, it could, for example, represent a scenario in which wind shells fragment because of Rayleigh–Taylor instabilities. Shell fragments then stream across the IGM without necessarily modifying the density and temperature of the regions responsible for most of the absorption features in the Lyman forest. Alternatively, if the effective clumping factor of the undisturbed IGM is large enough, much of it may avoid being swept up onto shells.

6 METAL EJECTION EFFICIENCY

Which galaxies produce the metals we observe in the IGM? To answer this question, we plot in Fig. 10 the cumulative distribution of metal mass in shells as a function of the stellar mass of the parent galaxies. Different curves are for different model parameters at $z = 3$.

Different parameter choices lead to different shapes for the distribution. Half of the metals appear to have been ejected from galaxies with intermediate to large stellar masses ($M_\star \gtrsim 10^8 M_\odot$). Galaxies with $M_\star < 10^8 M_\odot$ give a significant contribution only in models with $\varepsilon = 0.01$, where the total number of wind–blowing galaxies is higher than in all other models by a factor of five to ten, as shown in Fig. 4. Although models with $\varepsilon = 0.01$ clearly favour ejection from low stellar mass galaxies and at early times, there is no suppression of the efficiency of ejection from larger galaxies.

For comparison, in Fig. 11 we show the cumulative distribution of the stellar mass in galaxies, at $z = 3$. The contribution of galaxies with $M_\star < 10^7 M_\odot$ to the total amount of stars formed in our simulated region is negligible and no winds are powered by such objects. The shape of the distribution is similar to the one of the metal mass ejected in models with $\varepsilon = 0.01$.

Metals can be efficiently ejected by massive galaxies if their star formation activity is powerful enough to sustain an outflow. In models with a high entrainment fraction the energy input necessary to blow a wind out of a massive galaxy is often too large to be provided by quiescent star formation alone. On the other hand, quiescent star formation does succeed to power such outflows in models with $\varepsilon = 0.01$, where the energy required to overcome the gravitational attraction and the ram pressure of the ambient medium is smaller.

Mergers can provide a further key to understand why galaxies with intermediate and large masses play such an important role to pollute the IGM with metals in all our models. Satellites falling onto central galaxies may be powering a wind whose shell is accreted by the central galaxy, following the prescriptions in subsection 2.3.4. These merged shells receive a strong kick from the burst of star formation that follows the merger and the resulting wind energy may be easily high enough to allow the shell to escape the gravitational pull of the central galaxy.

In the top panel of Fig. 12 we plot the total mass of metals in shells, as a function of our model parameters. For comparison, we overplot the total mass of metals in our simulated region, as a thick dashed line. The metal mass accumulated in shells is sensitive to factors that depend on redshift. At $z > 3$ more metals are ejected for models with $\varepsilon = 0.01$, while at $z < 3$ metal ejection is more efficient for higher mass loading efficiency.

In the bottom panel of Fig. 12 we show the efficiency of metal ejection by galactic winds, which we calculate as the ratio between the metal mass ejected by winds, shown in the upper panel of Fig. 12, and the total amount of metals in stars and in the gaseous phases of galaxies, given by the thick dashed line in the same plot. In models with $\varepsilon = 0.01$, the efficiency is rather high at every redshift and remains almost constant with time. In these models, winds blow into the IGM about a third of the total mass of metals in galaxies. Models with $\varepsilon > 0.01$ favour ejection mostly at low redshifts, while metals are preferentially retained by galaxies at higher redshifts. In these models, the efficiency of the ejection increases steeply with time and at very low redshifts a large fraction of the metals produced in galaxies are ejected into the IGM. The metal ejection efficiency is not always higher for those winds which are best able to escape from galax-
Figure 12. Upper panel: the total metal mass contained in shells, as a function of redshift. For comparison, the thick dashed line represents the total mass of metals in our simulated region. Bottom panel: the fraction of metal mass in shells, as a function of redshift. The total mass of metals in our simulated region is calculated taking into account all the metals contained in stars and in the gaseous phases of galaxies. In both panels, the different lines correspond to different parameter choices as in Fig. 3.

In fact, at $z \lesssim 2$ we find that models with $\varepsilon > 0.01$, in which only about 25% of the galaxies blow winds, can eject more metals than models with $\varepsilon = 0.01$, in which most of the galaxies do have winds. About half of the synthesised metals are generally retained by galaxies at all redshifts.

In Fig. 13 we show the mean metallicity of shells in solar units, as a function of redshift. This depends on the ratio between the mass entrained in the shell from the metal–free IGM and the metal rich gas accreted directly from the wind. Of crucial importance is the ability of winds to travel far into the IGM, where they can accrete more mass from the IGM than from the wind.

The metallicity of shells may be an important indicator of the metallicity of the IGM, once the total amount of intergalactic gas affected by winds is known. The mean metallicity of the IGM may be roughly estimated by multiplying $f_m$ by the shell metallicity. At $z \sim 1$ to 4 our results overestimate the metallicity of the low density IGM, with respect to the observed values, by a factor of about 10–100. There are two possible explanations for this: either our model expels more metals into the IGM than actually happens in real galaxies, or the metals are really ejected but they are not mixed into the observed gas.

While our models might overestimate the total amount of mass and metals ejected by galaxies by a factor of up to a few, it is unlikely that such a correction would change our result that the mean IGM metallicity is well above the observed values. Thus, the discrepancy between the two values must be explained by the non–detection of the metals in winds and shells.

Why should we be unable to detect metals in the IGM? The C IV detected in the spectra of quasars is generally photoionised and its temperature is not higher than a few times $10^5$ K. For higher temperatures, collisional ionisation becomes efficient, so that carbon is fully ionised and does not absorb the UV photons anymore. The temperature of the wind shells, where we assume all the gas and metals are accumulated, may be a crucial factor in determining their observability in absorption. Our semi–analytic prescriptions for winds do not give any indication of this temperature, but, as a simple test, we can estimate it by using the radiationless shock model (Dopita & Sutherland 2002). As in our semi–analytic prescriptions for wind evolution, this model assumes that radiative losses are negligible. The temperature of the shocked gas in the shell is $T = 3\mu m_H v_s^2/16k$, with $\mu$ the mean molecular weight, $m_H$ the mass of atomic hydrogen, $k$ the Boltzmann constant and $v_s$ the shock velocity. Here we assume that the shock velocity is given by the difference between the wind and the shell velocity. For shock velocities in the range 150 to 500 km s$^{-1}$, the shell temperatures fall in the range between $10^6$ K and $10^7$ K.

In our simulations, most of the shells that have escaped the potential wells of haloes have velocities above 100 km s$^{-1}$, while the wind velocity is always higher than that by a factor of a few. According to the radiationless shock model, their temperatures are therefore generally high enough for collisional ionisation of carbon to take place. This simple calculation confirms the idea that the IGM is actually enriched to a higher level than observations prove, but that the metals blown out of galaxies by galactic winds are in most cases too hot to produce any absorption in the spectra of high redshift quasars.

The fraction of IGM mass involved in outflows is small but still significant, as proved by our calculations of $f_m$. Gas at temperatures as high as $10^7$ K is expected to emit radiation in the X–ray band and one would expect to find X–ray
emission in the IGM not associated with jets or collapsed objects. Indeed, X-ray emission from highly ionised metal species (O VIII and Ne X) in a warm–hot IGM (WHIGM) may have been recently discovered by CHANDRA (e.g. Nicastro et al. 2002, McKernan et al. 2003). This hot gas may be shock heated by galactic winds as well as from the process of structure formation or jets from active galaxies. If the first case is true, this gas may represent the hot metal enriched gas accumulated in our shells, which is too highly ionised to produce absorption in the Ly$\alpha$ forest.

7 THE ROLE OF GALAXIES WITH DIFFERENT MASSES

In this section we investigate the role of galaxies with different masses in polluting the IGM with metals, by comparing the results obtained from our four sets of simulations with increasing mass resolution. The same results can be obtained by running a version of M$3$ in which galaxies with halo masses lower than a fixed threshold are not allowed to blow winds. While a large population of dwarf galaxies is already forming at $z \lesssim 20$ in M$3$, only a few objects are assembling in M$2$ at the same epoch and in the lower resolution runs M$1$ and M$0$ the first galaxies appear only at $z < 15$ and $z < 7$, respectively. The total number of galaxies in M$3$ is five times as large as in M$2$ at $z = 0$ and the number of galaxies with winds six times as large.

In Fig. 14 we show the dependence of the volume filling factor (top panels), the fraction of mass in shells (mid panels) and the total metal mass in shells (bottom panels) on the mass resolution of the simulations. The left panels show the results for a model with high mass loading efficiency, while the right panels for a model with low mass loading.

In models with a high entrainment fraction, whose results are shown in the left panels, all quantities depend strongly on the mass resolution of the simulations and on the ability to resolve low mass galaxies. The left panels in Fig. 14 seem to imply that these galaxies are responsible for about half of the filled volume at $z = 0$ and an even larger fraction at higher redshifts, with similar results for the fraction of IGM mass in shells and for the ejected metals. However, a more detailed analysis reveals that the contributions of low stellar mass galaxies are always small with respect to the one from galaxies with $M_* \gtrsim 10^8$ M$_\odot$. This unintuitive behaviour arises from the fact that increasing the mass resolution does not only increase the number of galaxies with lower masses, but also makes it easier for larger ones to blow winds, by introducing new sources of energy input. The fraction of wind–blowing galaxies increases with increasing resolution, and so does, for example, the metal mass in shells contributed by large galaxies.

On the other hand, almost all galaxies with $M_* > 10^7$ M$_\odot$ blow winds in models with $\varepsilon = 0.01$. In these models, the mass and metal budget at $z \lesssim 3$ are dominated by winds driven by galaxies with stellar masses between a few times $10^8$ and $10^{10}$ M$_\odot$, mostly resolved by M$2$. The relative contributions of winds blowing out of galaxies with $M_* \gtrsim 10^{10}$ M$_\odot$ are larger than in models with higher mass loading, but at $z \sim 0$ still do not exceed a few percent. The role of massive galaxies in determining $f_{\nu}$, $f_m$, and the ejection of metals becomes more and more important with time. At $z \sim 0$, galaxies with $M_* < 2 \cdot 10^8$ M$_\odot$ contribute no more than about 20 to 30% to the volume filling factor. At $z < 2$, the galaxies with $M_* > 10^8$ M$_\odot$, resolved in M$2$, account for nearly half the fraction of IGM in shells and for about 90% of the total mass of metals ejected by winds. In these models, low mass galaxies are important for the chemical enrichment of the IGM at high redshifts, while at lower redshifts massive galaxies dominate.

One may ask if objects with stellar masses lower than about $10^7$ M$_\odot$ might give a substantial contribution to pollution of the IGM at redshifts where larger objects have not yet assembled. Indeed, Madau, Ferrara & Rees (1999) claim that the IGM has been polluted by outflows from pregalactic objects, with total masses well below $10^8 - 10^9$ M$_\odot$. In principle, winds may escape very easily the shallow potential wells of such objects, in a scenario where little mass is accreted onto the shell from the surrounding medium. On the other hand, winds would not escape at all in case of efficient mass loading, according to our model. Unfortunately, our simulations do not have sufficient resolution to follow the evolution of these objects.

At lower redshifts, the evolution of objects with total masses lower than $10^9$ M$_\odot$ may be affected by feedback effects that inhibit their star formation activity (e.g. Haiman, Rees & Loeb 1997, Mac Low & Ferrara 1999). As a result, these objects would be unable to blow winds, making their contribution to the pollution of the low redshift IGM negligible with respect to other galaxy populations with higher stellar masses.

8 CONCLUSIONS

We have presented semi–analytic simulations of galaxy formation in a cosmological context, which include the physics of galactic winds. The semi–analytic prescriptions are applied to high resolution N–body simulations of a typical “field” region of the Universe.

The dependence of the wind properties on our model parameters $K$ and $\varepsilon$ is investigated in section 3. The mass accumulated in shells is directly linked to the amount of mass entrained from the IGM, mostly set by $\varepsilon$, and the ultimate fate of winds is strongly dependent on this swept–up mass. The results of our models seem to fall broadly into two groups, as a consequence of the mass loading of shells. The first group includes all the models with $\varepsilon \gtrsim 0.1$, while models with $\varepsilon < 0.01$ belong to a different category. Shells that load little mass from the surrounding medium escape the gravitational potential well of their host haloes very efficiently at every redshift. These shells are mostly composed of metal rich supernova ejecta and shocked ISM and they need to spend little of their energy to accelerate the entrained gas. On the other hand, the formation of highly mass loaded winds is suppressed in galaxies with $M_* \lesssim 10^{10}$ M$_\odot$. The suppression is particularly strong in dwarf galaxies. In these models, the energy provided by star formation is not sufficient to overcome the ram pressure of the infalling material and the gravitational pull of the galaxy. In all our models, dwarf galaxies play a key role at $z > 3$, when larger objects have not yet assembled. However, their contributions become less important at later times, when more massive galaxies are formed.

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Figure 14. Dependence of $f_v$, $f_m$ and of the total metal mass in shells on the mass resolution of the dark matter simulations. In the left panels we show results for the model with parameters $\epsilon = 0.1$ and $K = 0.5$, while in the right panels for the model with $\epsilon = 0.01$ and $K = 0.1$. The two different behaviours are typical of two groups of model we identify in section 7. The lines represent respectively our four simulation sets: (1) thick solid line: M3, $M_p = 1.7 \cdot 10^9 h^{-1} M_\odot$; (2) dotted line: M2, $M_p = 9.5 \cdot 10^8 h^{-1} M_\odot$; (3) dashed line: M1, $M_p = 4.8 \cdot 10^8 h^{-1} M_\odot$; (4) dashed dotted line: M0, $M_p = 6.8 \cdot 10^9 h^{-1} M_\odot$.

We have estimated the volume filling factor of winds in section 4 and in section 5 we have calculated the fraction of IGM mass in shells, which gives a different view of how the IGM is affected by outflows. In general, low values of $f_v$ are associated with more mass loaded shells, while the opposite is true for $f_m$. The fraction of mass in shells is usually lower than the volume filling factor, suggesting that the actual fraction of intergalactic mass affected by outflows is small even when the winds physically fill a large region of space. The values of $f_v$ and $f_m$ suggest that winds are unlikely to significantly modify the properties of the Ly$\alpha$ forest.

We investigate the efficiency of winds in seeding the IGM with metals in section 6. In models with $\epsilon = 0.01$ winds from low stellar mass galaxies can efficiently pollute the IGM with metals at relatively high redshifts, while models with a higher entrainment fraction imply a later enrichment by more massive galaxies. This last result qualitatively agrees with the results of Aguirre et al. (2001). In the majority of the models, at least half of the produced metals are retained by galaxies.

Our estimates of the mean metallicity of the IGM are significantly higher than the observed values at $z \sim 1$ to $z \sim 5$ and we have argued that metals in the IGM might not be observable in absorption in the spectra of quasars because of the high temperatures induced in shells. Nonetheless, some shell material may turbulently mix with other
IGM gas and become subject to radiative cooling. The temperature of such shell material may therefore decrease until hydrogen recombines and the metals reach lower ionisation states, for example C IV, Si IV and O VI. In a forthcoming paper we will investigate possible observable signatures of galactic winds in the Ly$\alpha$ forest and we will discuss the possibility of finding absorption features due to cooled shells in the spectra of quasars.

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