DAMPED Lyα ABSORBER KINEMATICS AND OUTFLOWS FROM STARBURST GALAXIES

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Received 2008 August 19; accepted 2009 October 26; published 2009 November 25

ABSTRACT

We present results from a numerical study of the multiphase interstellar medium in sub-Lyman-break galaxy protogalactic clumps. Such clumps are abundant at $z = 3$ and are thought to be a major contributor to damped Lyα absorption. We model the formation of winds from these clumps and show that during star formation (SF) episodes they feature outflows with neutral gas velocity widths up to several hundred km s$^{-1}$. Such outflows might, in principle, produce the high velocity dispersion observed in damped Lyα absorbers (DLAs). Since the majority of DLAs have low SF rates, and only a small fraction of them might host a starburst at any given time, our median velocity width $v_{90}$ still falls short of the observed value. This discrepancy with observations could indicate that at $l = 12$ pc grid resolution the efficiency of conversion of feedback energy into hydrodynamical flows is less than optimal, even though these models show a remarkable improvement compared to the lower resolution runs. At $l = 24$ pc, the first signs of the multiphase medium are spotted; however, at this low resolution thermal injection of feedback energy cannot yet create hot expanding bubbles around star-forming regions—instead feedback tends to erase high-density peaks and suppress SF. At $l = 12$ pc, we see the formation of cold ($\lesssim 300$ K), dense ($\gtrsim 100$ $M_{\odot}$ pc$^{-3}$) clouds that maintain SF while being compressed by the hot medium; at the same time a large fraction of feedback energy is channeled into low-density bubbles and winds. These winds often entrain compact neutral clumps which produce multi-component metal absorption lines.

Key words: galaxies: formation – galaxies: kinematics and dynamics – intergalactic medium

Online-only material: color figures

1. INTRODUCTION

Current numerical galaxy formation models can successfully reproduce some of the properties of damped Lyα absorbers (DLAs), such as the lower end ($N_{\text{HI}} \lesssim 10^{21.5}$ cm$^{-2}$) of the column density distribution and the total incidence rate (Pontzen et al. 2008; Razoumov et al. 2008), the distribution of metals, and the slope of the relation between metallicity and low-ion velocity width which appears to originate in the mass–metallicity relation in the models (Pontzen et al. 2008). On the other hand, simulations tend to overpredict the number of DLAs with $N_{\text{HI}} \gtrsim 10^{21.5}$ cm$^{-2}$ and systematically produce fewer high-velocity systems. Most such systems feature multiple components in their absorption line profiles, but unfortunately one cannot map these components from the velocity space to real space to identify the absorption regions and constrain the mechanism producing such high velocities.

In general, the velocity dispersion of neutral gas clouds can come either from the gravitational infall in the process of hierarchical buildup of galaxies, in the form of random velocities of protogalactic clumps (Haehnelt et al. 1998), or from feedback from stellar winds and supernovae (SNe; Schaye 2001). In fairly massive $10^{12} M_{\odot}$ halos at $z = 3$ as much as 20%–30% of gas by mass can be in the cold phase surviving the infall (Razoumov et al. 2008). The corresponding $v_{\text{circ}} \sim 250$ km s$^{-1}$ can account for part of the observed neutral gas velocity dispersion. However, more massive halos are rare at $z = 3$, and the fraction of cold gas drops sharply in $>10^{12} M_{\odot}$ halos, leaving us in search of other mechanisms to produce high velocities.

Galactic winds driven by the feedback energy from stellar winds and SNe are an obvious candidate (Schaye 2001). Star-forming Lyman-break galaxies (LBGs) at $z \sim 3$ show evidence for large-scale outflows with typical velocities of hundreds km s$^{-1}$ (Pettini et al. 1998, 2001). In fact, with a simple semi-analytical model McDonald & Miralda-Escudé (1999) showed that feedback at the rate $1.8 \times 10^{39}$ erg yr$^{-1}$ per $10^{12}$ $M_{\odot}$ of halo dark matter mass added to the velocity dispersion of neutral clouds inside virialized halos works out perfectly to explain the observed DLA kinematics. However, this energy transfer takes place on pc scales currently inaccessible to cosmological models. Moreover, the inability of numerical galaxy formation models to capture physics on such small scales has led to a number of predicaments, the most famous of which is the overcooling problem, accompanied by the excessive loss of angular momentum in simulated galactic disks.

This classical problem (Katz 1992) has been somewhat alleviated in recent years (Thacker & Couchman 2000; Sommer-Larsen et al. 2003) as it was realized that feedback from young stars can be very efficient at keeping gas in a diluted state preventing it from rapid collapse and conversion into stars. However, even galaxy models at a sub-kpc (0.1–1 kpc) resolution cannot capture propagation of supernova blast waves into the interstellar medium (ISM), as the injected thermal energy is radiated away very quickly before it can be converted into kinetic energy. The reason is very simple: the mass of a resolution element to which the feedback energy is supplied is usually several orders of magnitude larger than the typical mass of a SN ejecta. Therefore, the temperature and expansion velocity of the post-shock regions are greatly underestimated, and so is the cooling time which scales as $\propto T^{1/2}$ above $10^5$ K (Dalla Vecchia & Schaye 2008). Cosmological simulations must then turn to ad hoc assumptions about the role of stellar feedback at scales below their resolution limit. Two types of solutions have been popular. The first one is suppressing radiative cooling in the feedback regions for the duration of the starburst (Mori et al. 1997; Thacker & Couchman 2000; Sommer-Larsen et al. 2003; Stinson et al. 2006) to allow more efficient conversion of feedback energy into...
hydrodynamical expansion. This approach leads to more realistic simulated galaxies that correctly reproduce many of the observed properties of present-day disks and have only a small deficiency in angular momentum. More recent simulations have shown that supernova feedback plays a fundamental role in formation of large stable disk galaxies, providing pressure support shown that supernova feedback plays a fundamental role in for-
deficiency in angular momentum. More recent simulations have
observed properties of present-day disks and have only a small
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selected hot phase particles (Scannapieco et al. 2006) is known
to produce “puffy” galaxies that cannot reproduce the high-end
tailed of the observed DLA velocity dispersion (Razoumov et al.
Since these galaxies extend to larger radii, their outer
regions may pick part of the velocity dispersion of the local
galaxy group, so that they have slightly less severe kinematics
problem (Pontzen et al. 2008) than similar resolution models
which do not suppress radiative cooling.

The second widespread approach is to use kinetic feedback
instead of thermal feedback (Navarro & White 1993; Springel &
Hernquist 2003; Dalla Vecchia & Schaye 2008), usually imple-
mentedit in particle-based simulations. Although there are several
variations of this method, the basic idea is to give a velocity kick
to a small fraction of gas particles near the star-forming regions,
adjusting the mass loading and velocities to reproduce observa-
tions. Some of the recipes turn off hydrodynamical interaction
of the wind particles with the gas to obtain large-scale outflows,
while others stress the importance of such interaction to create
hot bubbles in the ISM and develop galactic fountains (Dalla
Vecchia & Schaye 2008).

A popular method to circumvent some of the resolution
problems that can be combined with either of the above two
approaches is to use a sub-resolution multiphase model that
describes analytically growth of cold clouds embedded in a
hot intercloud medium, SF in these clouds, feedback and cloud
evaporation (Yepes et al. 1997; Springel & Hernquist 2003).
In such models SF and feedback are self-regulating. However,
different phases are not dynamically separated from each other,
and therefore by itself such model cannot result in
outflows.

At the other end of the resolution spectrum, detailed models
of small patches of galactic disks, usually in the context of the
Milky Way galaxy, provide sufficient resolution to study
turbulent ISM stirred by SN explosions. Such models resolve
hot bubbles driven by individual SNe, fragmentation of shells
created by these bubbles, and the structure of cold dense clouds
on pc scales (e.g., Joung & Mac Low 2006). High SF rates in
such models naturally lead to galactic outflows, galactic
fountains rising to several kpc away from the midplane, and shell
fragments raining back onto the disk as intermediate-velocity
cold clouds (Joung & Mac Low 2006). Such high-resolution
simulations can, in principle, be used to develop subgrid models
of stellar energy feedback for a given SF rate in cosmological
simulations, although to the best of our knowledge currently
there are no subgrid models in the literature that separate the
dynamics of different components of the ISM.

In the past few years, it has become possible to extend
such high-resolution three-dimensional (3D) models to entire
galactic disks, albeit at a lower spatial resolution. Tasker &
Bryan (2006) used adaptive mesh refinement (AMR) models
to study the multiphase ISM in a quiescent Milky Way-sized
disk galaxy. They employ two SF prescriptions, one based on
cosmological simulations, with low SF threshold (0.02 cm\(^{-3}\))
and low efficiency, and the other one with a much higher
threshold (10\(^3\) cm\(^{-3}\)) and a high efficiency. Their highest
numerical resolution is 25 pc which is a typical size of giant
molecular clouds; they include cooling to 300 K and later add
photoelectric heating (Tasker & Bryan 2008). Their models
produce a multiphase ISM with most of the mass in cold,
dense clouds, while SN feedback drives gas out of the plane
of the galaxy, but most of it eventually falls back on the disk.
All of their models reproduce the slope of the observed relation
between the SF rate and the gas surface density, on both global
and local scales, although the high-density threshold models
tend to produce more intermittent outflows and occasionally
triggered SF in the outer disk.

Saitoh et al. (2008) carried out smoothed particle hydrodynam-
ics simulations of an isolated gas disk with 10\(^8–10^9\) particles
to study the effect of various SF prescriptions on the structure of
the ISM. Similar to Tasker & Bryan (2006, 2008), they test both
a cosmological (0.1 cm\(^{-3}\)) and a high-density (100 cm\(^{-3}\)) SF
thresholds, but also vary the SF efficiency \(\epsilon_{SF}\). Only the high-
density threshold models could reproduce the complex multi-
phase structure of the gas disk, regardless of the value of \(\epsilon_{SF}\). In
these runs, the SF rates depend on the modeled global gas flow
from intermediate densities to the actual sites of SF rather than
the actual prescribed SF efficiency. On the other hand, the low-
density threshold models produce thicker and smoother disks
with SF rates highly sensitive to the chosen value of \(\epsilon_{SF}\).
Therefore, they conclude, the use of a high SF threshold will avoid
uncertainties in the SF models.

Ceverino & Klypin (2009) developed a realistic prescription
for modeling feedback formulating conditions under which
simulations would resolve the formation of hot bubbles in the
multiphase ISM. Such bubble can only be created if simulations
resolve cold dense clouds in which feedback occurs—only in
these clouds heating can exceed cooling so that a large fraction
of feedback energy is converted into hydrodynamical expansion,
creating the hot phase and driving winds. Ceverino & Klypin
(2009) also added heating by massive binary systems which are
ejected from molecular clouds when one of the components be-
comes a SN. These “runaway stars” carry energy very efficiently
away from high-density regions, eventually exploding as SNe in
lower density environments and thus facilitating the formation
of the hot gas component even in low-resolution cosmological
models.

In this paper, the approach of Ceverino & Klypin (2009) is
used to study the formation of winds in high-redshift proto-
galactic clumps responsible for damped Ly\(\alpha\) absorption. We
show that a brief episode of SF in a sub-LBG galaxy that
creates a multiphase medium can also drive winds with neutral
gas velocity dispersions up to several hundred km s\(^{-1}\).
If a substantial fraction of \(z = 3\) protogalactic clumps form
such winds at any given time, these winds can explain the ob-
served DLA kinematics (Schaye 2001). Our models resolve
the effect of massive stars in protogalactic clumps. Although
the spatial resolution of this study (12 pc) is not sufficient to
follow the details of shell fragmentation or turbulent interac-
tions, it is argued that this resolution is adequate for modeling
the multiphase medium for the purposes of computing galaxy
formation and launching galactic winds in the cosmological
context.
2. MODELS

2.1. Peak Cross-section of DLA Absorption

The mass range of halos that are the main contributors to the total DLA line density is still debated. Pontzen et al. (2008) argue that the main contribution comes from halos in the mass range $10^{10} - 10^{11} M_\odot$. Lower mass halos have much smaller absorption cross-sections due to heating by the ultraviolet background (UVB), while the number of halos with masses above $10^{11} M_\odot$ drops sharply. Pontzen et al. (2008) point out that their peak at $\sim 10^{10} M_\odot$ is probably related to their particular feedback implementation in which cooling is turned off to reproduce the blast wave solution. On the other hand, Nagamine et al. (2007) see a peak of DLA absorption shift to higher halo masses with the increased wind strength, reaching $\sim 10^{12} M_\odot$ in the “strong wind” model.

In our earlier cosmological DLA models (Razoumov et al. 2008), the most common DLA absorbers are halos in the range $10^{10} - 10^{11.5} M_\odot$. At the lower end of this range, absorption is typically dominated by a single galaxy in the halo, while in halos with masses above $\sim 10^{11} M_\odot$ DLAs are commonly associated with one of the several protogalactic clumps with the average gas clump mass of $\sim (1-2) \times 10^9 M_\odot$ (Figure 1). The motion of clumps within a larger halo does not provide the large observed velocity dispersion. Can outflows from star-forming regions in these clumps produce such dispersion? The current paper attempts to answer this question by modeling formation of winds in one of these clumps as it undergoes a starburst. We adopt a fixed gravitational potential with $M_{\text{halo}} = 3 \times 10^{11} M_\odot$ but consider a very low-mass disk with $f_{\text{disk}} = M_{\text{disk}} / M_{\text{halo}} = 0.005$ which is much lower than both the universal baryon fraction of $\sim 0.1$ and the upper value for galactic disks of 0.05 in Mo et al. (1998), reflecting compactness of such clumps.

In smaller ($10^{10} - 10^{11.5} M_\odot$) galaxies at $z = 3$, the supply of gas potentially available to form stars is limited by the infall rate onto disks, since the cooling time of pre-enriched gas in such halos is expected to be shorter than the infall time (White & Frenk 1991). In other words, the gas supply is essentially decoupled from the thermal evolution of the halo, and, therefore, we do not need to include a hot halo into our disk models. Such halo effectively forms when star-forming regions dump energy into the surrounding gas via winds and supernovae. Since we do not include gas accretion either into our present model, the total stellar mass of the disk will be limited by the initial amount of gas in the model.

2.2. Initial Setup and Grids

All simulations in this paper were performed using the AMR hydrodynamical code ENZO (O’Shea et al. 2005). The computational domain is a 3D periodic box 100 kpc on a side covered with a $64^3$ root grid and up to seven levels of refinement corresponding to 12 pc spatial resolution. A fixed spherical Navarro–Frenk–White dark matter profile

$$M_{\text{DM}}(r) = M_{\text{halo}} \frac{\ln(1 + x) - x/(1 + x)}{\ln(1 + c) - c/(1 + c)}$$

is assumed at the center of the volume, where $x = cr/r_{\text{vir}}$, the concentration parameter $c = 12$, and $M_{\text{halo}} = 3 \times 10^{11} M_\odot$. The initial distribution of gas follows an isothermal disk with a temperature of $10^4$ K and a density

$$\rho(r, z) = \rho_0 e^{-r/r_0} \text{sech}^2 \left( \frac{z}{2z_0} \right)$$

### Figure 1. H$^1$ column density map of the most massive halo in model M1 in Razoumov et al. (2008) at $z = 3$ (see the text for details). The projection is approximately 100 kpc on a side. The color scale is to the base-10 logarithm, and column density is measured in cm$^{-2}$.

Since our disks are at least 30 times smaller than the side of the box, using a small 100 kpc volume is a reasonable approximation; in addition, small perturbations from nearby clumps should be always expected. To resolve the initial disk configuration, inside the central (20 kpc)$^3$ region a hierarchy of six centered nested grids is set, with the maximum initial resolution of 24 pc. We start with the uniform temperature $T = 10^4$ K, resolving the Jeans length everywhere in the disk. During evolution we refine adaptively by the local Jeans length requiring that it must be resolved by at least 16 cells at all times, which is 4 times better than the Truelove criterion (Truelove et al. 1997).

A cooling function in the temperature range $T = 300 - 10^9$ K is assumed, with heating by the ionizing UVB from Razoumov et al. (2006) with self-shielding above 0.01 cm$^{-3}$. Solar metallicity is used in most our calculations; an additional model at 10% solar metallicity is also included.

2.3. Star Formation and Feedback

Star formation is modeled with discrete stellar particles that represent a population of stars born in the same cell roughly at the same time and assumed to have the same velocity vector in later evolution. In three of the four runs presented in this paper, we adopt the minimum stellar particle mass $M_{\text{s, min}} = 100 M_\odot$; our stellar particles can have any mass above $M_{\text{s, min}}$ if a sufficient amount of gas in a given cell satisfies the following
SF criteria. A stellar particle is always created at the finest local level of refinement, in cells in which (1) the total gas density exceeds the threshold \( \rho_{\text{SF}} \), and (2) the mass of the gas is larger than the local Jeans mass. In other words, stars will be formed only in cells in which the local Jeans length is unresolved which with our refinement criterion is possible only at the highest AMR level. If a cell is marked as a candidate for SF, we compute the mass of stars it would form with the given efficiency \( \epsilon_{\text{SF}} \) over the local dynamical time \( t_{\text{dyn}} \), and scale that mass to the local time step \( \Delta t \). If \( \rho(\Delta x)^3 \epsilon_{\text{SF}} \Delta t/t_{\text{dyn}} \) exceeds \( M_{\text{s, min}} \), a stellar particle is created, and the corresponding mass is removed from the gas component. Since our minimum stellar particle mass is very low and would allow us to record individual core-collapse SN events, we adopt instantaneous conversion of gas into stars with \( \epsilon_{\text{SF}} \), unlike, e.g., in Tasker & Bryan (2008) where the actual SF and feedback associated with each stellar particle are continuous over the dynamical timescale.

Over its lifetime every stellar particle injects feedback energy into the thermal energy of the gas. We use a prescription similar to that of Ceverino & Klypin (2009) to include feedback by both stellar winds and type II SNe. The total energy release is computed assuming a Miller–Scalo initial mass function (4) over its lifetime every stellar particle injects feedback energy into regions which have been cleared by winds and type II SNe. The total energy release remaining energy is assumed to be contributed by stellar winds and type II SNe. The total energy release \( n \) for a mass range \( 10^3 \) to \( 10^8 \) is computed assuming a Miller–Scalo initial mass function and feedback associated with each stellar particle are continuous over the dynamical timescale.

In addition to energy, winds and SNe also return mass and metals to the ISM. In our models, energy and mass release into the ISM is strictly synchronized to avoid putting too much energy into regions which have been cleared by winds and/or earlier SNe. We assume that \( n_{\text{mass}} = 0.25 \) of the total mass that goes into stars is ejected back into the ISM via winds and SNe. An upper estimate of the gas temperature in low-density feedback regions can be derived by considering the limiting case in which all energy goes to heat the ejected mass \( n_{\text{mass}} M_* \). From the energy balance

\[
\frac{3}{2} k T \frac{n_{\text{mass}} M_*}{m_p} = \eta_{\text{tot}} M_* c^2,
\]

we can derive an upper limit for the sound speed in hot bubbles

\[
c_s \leq \left( \frac{k T}{m_p} \right)^{1/2} \approx \left( \frac{\eta_{\text{tot}}}{n_{\text{mass}}} \right)^{1/2} c \approx 1700 \text{ km s}^{-1},
\]

where \( c \) is the speed of light. The maximum theoretical temperature in feedback regions is then of order \( \sim 4 \times 10^8 \) K. Actual temperatures in hot bubbles are somewhat lower in the range \( 10^6 \)–\( 10^8 \) K, largely due to expansion and the work performed to compress the ambient medium, and to a much lesser degree due to cooling in the bubble itself. With outflow velocities added to \( c_s \), the Courant–Friedrichs–Lewy (CFL) condition sets the shortest time steps in our models to several thousand years.

All runs presented in this paper assume the SF efficiency \( \epsilon_{\text{SF}} = 0.3 \). Many authors have found that the exact value of \( \epsilon_{\text{SF}} \) has little impact on the mean SF rates (e.g., Stinson et al. 2006), as long as it is in the range from 0.05 to 1 (see their Figure 14). On the other hand, Governato et al. (2007) found that the SF efficiency affects the properties of smaller galaxies and that only runs with low \( \epsilon_{\text{SF}} < 0.1 \) can produce disks that are thin enough to match observations. We reran our main model A1 (Table 1) with \( \epsilon_{\text{SF}} = 0.06 \) and found a slightly lower SF rate that peaks at \( t = 110 \) Myr and gradually falls off over the next few hundred megayears. However, we found no visible change in the disk thickness and only a very slight reduction in wind velocities at the peak of outflows compared to A1, and therefore we do not include this model in the paper. The true efficiency of SF, i.e., the fraction of gas that is eventually converted into stars in dense clouds should be determined by an interplay of various processes starting from the hydrodynamical timescale of gas supply to the star-forming regions. Saioh et al. (2008) have found that at sufficiently high \( \rho_{\text{SF}} \) the SF rates are effectively set by the timescale of cold gas supply from reservoirs (\( n_{\text{H}} = 1 \) cm\(^{-3} \)) to the star-forming regions (\( n_{\text{H}} \geq 100 \) cm\(^{-3} \)) which in their calculations is about 5 times longer than the local dynamical timescale in the star-forming regions.

In this paper, we are using a set of four simulations listed in Table 1: a high-resolution starburst model A1, a high-resolution quiescent disk model A2, a low-resolution model A3 for which \( \rho_{\text{SF}} \) was adjusted to produce the highest SF rate, and a high-resolution model A4 at 10\% solar metallicity. The high-resolution models used seven levels of AMR in the (10 kpc)\(^2 \times 6 \) kpc region centered on the disk resulting in 12 pc grid resolution. The low-resolution model employed six levels of refinement in the same region corresponding to 24 pc spatial resolution.

We ran the quiescent model to estimate the effect of SF on the structure of the ISM and on galactic wind kinematics. There are two ways to reduce the SF rate in our models: increase the SF density threshold \( \rho_{\text{SF}} \), or increase the minimum stellar particle mass \( M_{\text{s, min}} \). Note that \( M_{\text{s, min}} \) is purely a computational parameter which sets the mass of a stellar particle in the code allowing us to limit the total number of particles. However, one should be careful in choosing the value of \( M_{\text{s, min}} \) since it is not independent of \( \rho_{\text{SF}} \). A star particle is formed only if \( \rho(\Delta x)^3 \epsilon_{\text{SF}} \Delta t/t_{\text{dyn}} \) in a cell exceeds \( M_{\text{s, min}} \). For the fiducial value \( \rho_{\text{SF}} = 158 M_\odot \text{ pc}^{-3} \) and \( \epsilon_{\text{SF}} = 0.3 \), the gas mass in a cell allowed to form stars is

\[
M_{\text{s, cell}} = 270 M_\odot \left( \frac{\rho}{158 M_\odot \text{ pc}^{-3}} \right) \left( \frac{\Delta t}{2000 \text{ yr}} \right).
\]

### Table 1: Simulation Parameters

| Model | \( \rho_{\text{SF}} \) (\( M_\odot \) pc\(^{-3} \)) | \( M_{\text{s, min}} \) (\( M_\odot \)) | Metals |
|---|---|---|---|
| A1 | 7 | 158 | 100 | 1 |
| A2 | 7 | 158 | 1000 | 1 |
| A3 | 6 | 25 | 100 | 1 |
| A4 | 7 | 158 | 100 | 0.1 |

**Notes.** (1) Highest level of refinement \( \Delta V_{\text{max}} \), (2) SF threshold \( \rho_{\text{SF}} \), (3) minimum stellar particle mass \( M_{\text{s, min}} \), and (4) metallicity relative to solar.
Figure 2. Total SF rates in all four runs sampled at 3 Myr time intervals.

Figure 3. Disk surface density of models A1, A2, A3, and A4 (clockwise starting from upper left) at $t = 119$ Myr. The color scale is to the base-10 logarithm, and surface density is measured in g cm$^{-2}$.

3. RESULTS

3.1. Global ISM Morphology

Without cooling our disks would be marginally Toomre-unstable. Adding cooling leads to rapid gas accumulation near the galactic midplane and its subsequent fragmentation into cold clumps and warm interclump material. For the initial central disk density $10^{-22}$ g cm$^{-3}$ and temperature $10^{4}$ K, the cooling time is of order of $10^{7}$ Yr leading to disk collapse onto the midplane in the first $\sim 20$ Myr. Soon thereafter first cold clumps form in which SF begins. At $\sim 50$ Myr the high-resolution models start developing a complex ISM morphology characterized by dense clouds and filaments separated by warm ($10,000$–$20,000$ K) medium seen in many simulations (e.g., Wada & Norman 2001), and to a lesser degree in the low-resolution model. In model A1 ample gas supply quickly leads to a starburst starting at $t \approx 50$ Myr and lasting $\sim 80$ Myr (Figure 2) in which $\sim 20\%$ of the gas in the disk is converted into stars. In the quiescent disk model A2, there is no single starburst phase; the first significant episode of gas conversion into stars takes place well past $t = 100$ Myr, with intermittent SF throughout the entire run. It is interesting that by the end of simulation A2 at $t \approx 420$ Myr approximately the same total stellar mass ($3 \times 10^{8} M_{\odot}$) is accumulated, although its effect on the underlying gas distribution will be completely different.

The morphology of the ISM is clearly affected by feedback from SF as can be seen from the surface density maps in Figure 3 at $t = 119$ Myr, toward the end of the starburst phase in model A1. By this time in the starburst model a large amount of mass and energy have been injected through feedback into the lower density gas. The result is a much larger role of pressure confinement of cold clouds in model A1, as opposed to more gravitational confinement in the quiescent model. The

Setting $M_{*\text{,min}} = 100 M_{\odot}$ (or any value below that in Equation (6)) would result in immediate SF once the density exceeds $\rho_{\text{SF}}$, whereas using a much higher value would artificially delay SF until more gas accumulates in the cell. For the quiescent disk model we use $M_{*\text{,min}} = 1000 M_{\odot}$. This prescription ultimately results in conversion of approximately the same amount of gas into stars, but over a several times longer period, and produces a very different ISM morphology and much weaker winds.
mass distribution appears to be smoother in the starburst model, with a lower density contrast between the clumps and the voids (Figure 4). Also evident in model A1 is a more pronounced gas accumulation near the galactic center, and a violent stripping of the outer gas regions of the disk by feedback waves. The latter process depends, of course, on the gas mass of the outer disk which in turn is determined by the cosmic accretion which we do not compute in our current models.

In the low-metallicity run A4 lower cooling leads to a smaller gas fraction in the cold phase, 20% versus 40% by volume near the midplane after the start of SF. However, the overall morphology of the ISM is remarkably similar to that of A1 (Figure 3), with the complex multiphase medium starting to develop around 50 Myr. The rise of the hot component follows SF which is delayed by some 10–20 Myr relative to A1 (Figure 2). In addition, a larger gas fraction in A4 can be found in the warm component which on average occupies close to half of the volume near the galactic midplane.

In the high-resolution models, dense clouds are continuously being formed and destroyed by self-gravity, differential rotation, feedback from SF inside the clouds, and interaction with feedback waves coming from nearby star-forming regions. Any single cloud usually survives only for a fraction of its galactic orbit revolution, in other words, from few megayears to few tens of megayears. This is consistent with many estimates of the giant molecular cloud (GMC) lifetimes in the Milky Way galaxy, although we do not resolve the scales and processes taking place inside these clouds.

3.2. Conditions in Simulated SF Regions

We are interested in modeling conditions in the star-forming regions that facilitate launching of galactic winds from thermal feedback only, without suppression of cooling. We will here review a set of criteria necessary to model winds and expanding hot bubbles in the ISM. First and foremost, heating by a SN must lead to a sharp rise in the gas temperature that would drive the hot bubble expansion without rapid cooling. In other words, during all stages of bubble expansion heating must dominate over radiative cooling. For the early stages, this condition was elegantly formulated in Ceverino & Klypin (2009, see their Equation (5)); using our SF threshold, we will write it as

\[ \Gamma \gtrsim 7.8 \times 10^{38} \, \frac{\text{erg}}{\text{cm}^2 \cdot \text{s}} \left( \frac{\rho}{158 \, M_\odot \, \text{pc}^{-3}} \right) \left( \frac{\Lambda}{10^{-22} \, \text{erg/cm}^3 \cdot \text{s}} \right) \left( \frac{\rho_s}{\rho} \right)^{-1}, \]

where \( \rho_s \) is the spatial density of young stars, and \( \rho_s / \rho \) is expected to be in the range 0.1–1. If the gas temperature is around \( 10^4 \, \text{K} \), cooling \( \Lambda \sim 10^{-22} \, \text{erg/cm}^3 \cdot \text{s} \), and heating from SNe cannot counterbalance cooling in any moderate overdensity. On the other hand, at very low temperatures (\( \sim 100 \, \text{K} \)) cooling is much less efficient (\( \Lambda \sim 10^{-25} \, \text{erg/cm}^3 \cdot \text{s} \)), and even at high star-forming cloud densities feedback may be able to heat the gas. Therefore, Ceverino & Klypin (2009) argue, it is crucial to include cooling to \( \sim 100 \, \text{K} \) to resolve the cold phase in order to heat up the gas via SN feedback. Once hydrodynamical expansion of the feedback region begins, gas flows out, the mass ratio \( \rho_s / \rho \) increases, assisting further heating and expansion.

When a SN injects energy into the ISM, the resulting pressure in the hot bubble greatly exceeds the surrounding pressure.

Provided that the energy is not quickly radiated away, the bubble expands only if it is not confined by self-gravity. This second condition was formulated in Ceverino & Klypin (2009) in terms of the pressure difference between the bubble and the
surrounding gas
\[ \Delta p \gtrsim \frac{4\pi G}{3}(\rho r)^2, \tag{8} \]
where \( r \) is the radius of the bubble, and \( \rho \) is the ambient gas density. Using the ideal gas equation of state and our SF density threshold, we can rewrite Equation (8) to obtain the minimum resolution necessary to model the expansion of the \( \text{H} \text{II} \) regions against self-gravity
\[ \Delta x \sim 2r \lesssim 14 \text{ pc} \left( \frac{T}{10^4 \text{ K}} \right)^{1/2} \left( \frac{\rho}{158 \ M_\odot \text{ pc}^{-3}} \right)^{-1/2}. \tag{9} \]

Since our models start to resolve individual SNe, the mass of a resolution element should be small enough in order for it to get heated by the typical \( \sim 10^{51} \text{ erg} \) explosion energy. A single SN explosion in a dense cloud may have a hydrodynamical impact only if it can heat its host cell to high \( (10^6-10^8 \text{ K}) \) temperatures of an expanding hot bubble. In other words, the energy input per SN should then exceed
\[ E_{SN} \gtrsim \frac{3\rho (\Delta x)^3}{2\mu m_H} kT, \tag{10} \]
which gives us an estimate of the minimum resolution necessary to heat up the host cell
\[ \Delta x \lesssim 2.49 \text{ pc} \left( \frac{E_{SN}}{10^{51} \text{ erg}} \right)^{1/3} \left( \frac{\rho}{158 \ M_\odot \text{ pc}^{-3}} \right)^{-1/3} \left( \frac{T}{10^6 \text{ K}} \right)^{-1/3}. \tag{11} \]

At first glance, this constraint requires much higher resolution than the self-gravity condition (Equation (9)). Fortunately, type II SN explosions have a 30–40 Myr delay after the initial starburst, and many of them explode in environments which have been previously cleared by stellar winds and neighboring SNe. Even more importantly, the lifetimes of individual cold clouds are usually in the range from few megayears to few tens of megayears. By the time a stellar particle hosts a SN explosion, its cloud of origin is very likely to have been destroyed, and the SN energy is released into a \( \rho \ll \rho_{SF} \) environment. In addition, stellar particles may have non-negligible intrinsic velocities—traveling even a small 5 km s\(^{-1}\) velocity for 35 Myr will take a particle 180 pc away from its birthplace. Therefore, the ISM densities in which type II SN explosions take place are likely to be several orders of magnitude smaller than \( \rho_{SF} \) making the constraint in Equation (11) much less demanding.

Once conversion of feedback energy into hydrodynamical expansion becomes efficient, lack of spatial resolution can present an additional problem. If the density contrast in the ISM is not resolved in the simulation, heating and hydrodynamical stirring of the star-forming clouds might erase high-density peaks bringing the ongoing SF to a halt. In other words, SF/feedback can be too self-regulating at low resolution. Since we do not know a priori the amount of clumping in the ISM at \( z = 3 \), perhaps the most reliable way to reduce this effect is to compare the SF rates at various resolutions.

### 3.3. Neutral Gas Kinematics in Quasar Absorption Lines

Figure 5 shows the \( \rho - T \) diagram of the entire simulation volume in all four runs at \( t = 119 \) Myr. Each plot is divided into 200\(^2\) cells, and each cell is colored by its mass fraction (darker means a higher mass fraction).

Assuming that winds remove all ambient gas, the minimum density in such cells can be easily estimated from the mass-loss rate of each star particle of mass \( M_* \) during its feedback stage
\[ \rho_{low} \approx \frac{0.25 M_*}{40 \text{ Myr} \Delta x} \left( \frac{\Delta x}{12 \text{ pc}} \right) \lesssim 8.6 \times 10^{-5} \text{ cm}^{-3} \]
\[ \times \left( \frac{v_{flow}}{1000 \text{ km s}^{-1}} \right)^{-1} \left( \frac{M_*}{100 \ M_\odot} \right) \left( \frac{\Delta x}{12 \text{ pc}} \right)^2, \tag{12} \]
Figure 6. \(v_{90}\) absorption velocity widths of low-ionization lines in four models as a function of time. The solid line in each panel shows the median velocity. The dashed horizontal line indicates the observed 90 km s\(^{-1}\) DLA median velocity.

where \(v_{\text{flow}}\) is the fiducial outflow speed, and \(\Delta x\) is the cell size. These feedback regions can be easily seen in the starburst model in Figure 5 at \(T \sim 10^6\) K, and to a much lesser degree in the quiescent model.

Since we model isolated systems without external accretion, winds from the disk do not experience any ram pressure of the infalling material and can be stopped only by gravity and collision with the gas previously blown off the disk. The wind speeds often exceed several hundred km s\(^{-1}\), consequently a large fraction of the volume is quickly filled by a low-density (\(\sim 10^{-4}\) cm\(^{-3}\)) gas (Figure 5). Since we model a large (100 kpc) computational volume, the mass fraction locked in this low-density component is significant, especially in the quiescent model A2. In the starburst model A1, the density of the wind is clearly much higher (Figure 5). Can such dense winds from...
starburst environments account for the wide absorption line profiles seen in DLAs?

To answer this question, we constructed a set of low-ionization metal line spectra. At each time output, we projected 200 random lines of sight within 3 kpc of the center of each disk and calculated absorption line profiles of an unsaturated low-ion transition along sight lines with H\textsc{i} column density above $10^{20.3}$ cm$^{-2}$. For each such profile, we calculated a line width $v_{90}$ corresponding to 90% of the total optical depth of all components in the line. Note that this diagnostic measures the neutral gas velocity dispersion, not the typical outflow velocities, and is dominated by clouds with large optical depths. Its more detailed discussion and the comparison to the equivalent width can be found in Prochaska et al. (2008). Figure 6 shows the distribution of $v_{90}$ widths for each model as a function of time, along with the median value. Although these velocities cannot be compared to DLAs statistics directly, since we do not have a cosmological sample and do not account for gas accretion which would regulate SF episodes, we note that at solar metallicities (models A1–A3) the typical absorption velocities are the highest in the starburst model A1. None of the cosmological DLA models can reproduce the observed median $\langle v_{90} \rangle \approx 90$ km s$^{-1}$, with the actual value of $\langle v_{90} \rangle$ of order 40–50 km s$^{-1}$ in Razoumov et al. (2008) and close to 60 km s$^{-1}$ in (Pontzen et al. 2008). Note that in cosmological models the simulated widths are also sensitive to the DLA cross-sections, as, for instance, the velocity dispersion in “puffy” galaxies with extended radial profiles will have an additional weight.

We argue that if a substantial fraction of clumps along the quasar line of sight in a host halo experience an active starburst, it could result in a much larger velocity dispersion possibly explaining the observed incidence rate of high-velocity DLAs. The fraction of such active star-forming galaxies is poorly constrained and in cosmological simulations can be only computed from the cosmic gas infall rate onto galaxies.

Here instead we focus on outflows from individual protogalactic clumps. In the starburst model, A1 $\langle v_{90} \rangle$ is close to the observed value from $t = 80$ Myr to 120 Myr, whereas the quiescent model has $\langle v_{90} \rangle \approx 50$ km s$^{-1}$ for most of its evolution, resembling the velocity widths in cosmological simulations. The low-resolution model A3 features a delayed and much weaker SF with $\langle v_{90} \rangle$ briefly reaching 70 km s$^{-1}$. The low-metallicity run A4 shows velocity widths with a trend similar to the integrated line widths.

Figure 8. Median (filled circles) and mean (open triangles) $v_{90}$ absorption velocity widths as a function of the SF rate in the starburst model A1.

Figure 9. Edge-on slice through the disk of model A1 at 119 Myr showing gas density (top panel, log($n_{\text{H}}$/ cm$^{-3}$)) and temperature (bottom panel, log($T$/K)). (A color version of this figure is available in the online journal.)
lar to A1, following the initial burst of SF, but peaking at a lower value $v_{90} \sim 80$ km s$^{-1}$ at $t = 110$ Myr. Further insight into the origin of the velocity dispersion can be obtained from Figure 7 which illustrates the time evolution of the volume fractions of cold, warm, and hot gas in the plane of the disk. After very rapid cooling the early ($t < 50$ Myr) evolution is marked by separation of gas into warm and cold components. Shortly thereafter feedback gives rise to the hot component, and subsequent evolution of the disk is characterized by recurrent episodes of gas heating and cooling. The “depth” of these episodes is higher in the low-resolution model, in which relatively low-density cold clumps are more susceptible to feedback. At high resolution (A1, A4) the relative change of the volume fraction of cold gas is visibly reduced, as the number of cold star-forming clumps increases, and so does the density in individual clumps. The higher SF rate results in a larger volume filling fraction of the hot gas, at the same time driving more energetic winds from the disk.

It is useful to plot the relation between the SF rate and outflow velocities (Figure 8). A correlation is clear: a higher SF rate leads to faster outflows. These numbers reflect the trend seen in low-ionization absorption lines in local dwarf starburst galaxies (Schwartz & Martin 2004; Schwartz et al. 2006, see their Figure 12), although observational uncertainties and variations in individual galaxies are fairly high.

We can see the formation of hot galactic chimneys driving the outflows in the vertical slice in Figure 9. The visual structure of the outflows is very different from the single-source models of winds from high-redshift dwarf galaxies (e.g., Fujita et al. 2004), more resembling the high-resolution multiphase models of Ceverino & Klypin (2009) and Wada (2008). Our current spatial resolution is not yet sufficient to model instabilities in the shells created by hot bubbles (Ferrara & Ricotti 2006) or even follow these shells farther away from the disk.

Figure 10 shows the range of velocities and densities in the wind in the starburst model. Ionized, low-density wind moves with velocities up to several thousand km s$^{-1}$, whereas neutral gas exhibits velocities of few hundred km s$^{-1}$. Cold gas absorption comes from $|z| \lesssim 3$ kpc; there is a clear asymmetry above and below the disk, explained by the fact that feedback starts in a fairly small number of cold clumps. This asymmetry can also be seen in the H I column density maps in Figure 11. It is important to remember that since our models do not account for interaction of winds and shells with the infalling material,
the extent of the H\textsubscript{i} absorbing regions might change in more realistic models with cosmic infall.

4. DISCUSSION AND CONCLUSIONS

We use high-resolution hydrodynamic simulations of isolated $z = 3$ protogalactic clumps to show for the first time that the high-end tail of the DLA neutral gas velocity width distribution can in principle be produced if a substantial fraction of clumps in $10^{10}$–few $\times 10^{11} M_\odot$ halos experience a starburst event at the rate of few $M_\odot$ yr$^{-1}$. Such starbursts would generate a multiphase ISM in which the volume fraction of the hot gas exceeds 50% in the midplane of the clump. Hot bubbles created by feedback expand both in the horizontal direction to fill the interclump material, and vertically to form chimney-like structures which lead to high-velocity winds. Shells and neutral gas fragments embedded in such winds 1–3 kpc above the disk give rise to neutral gas absorption with the median velocity width at times approaching the observed value of $(v_{\text{90}}) \approx 90$ km s$^{-1}$.

However, the outflows from individual clumps in our simulations do not automatically translate into the observed velocity dispersion. In fact, we made a quick estimate of the potential impact of these models on cosmological $v_{\text{90}}$ by replacing all DLA systems in the 8 Mpc run M1 in Razoumov et al. (2008) with the starburst model A1 at the peak of outflows at $t = 120$ Myr which resulted in $v_{\text{90}}$ of only $\sim 74$ km s$^{-1}$. Having simultaneous starbursts in all clumps is clearly unrealistic, as the inferred SF rates in DLAs are similar to those in local dwarf galaxies, well below 1 $M_\odot$ yr$^{-1}$, much lower than the SF rates in LBGs or submillimeter galaxies at high redshifts (Hopkins et al. 2005). It has been recently suggested (Wolfe 2007; Wolfe et al. 2008) that a fraction of DLAs might host centrally located LBGs that would explain their high metallicities and high gas heating rates. The outflows from these galaxies could stir the central regions of their host DLAs, although it is not clear how much these objects could contribute to the overall statistics.

The discrepancy with observations is most likely due to an understimation of the outflow velocities for the considered SF rates in this paper. At 12 pc grid resolution, our models only barely resolve hydrodynamical expansion of hot bubbles into the ISM. The amount of gas which is being heated is probably too large, meaning that our simulations might still suffer from overcooling in feedback regions. We also note that the median velocity width in model A1 at $t = 250$ Myr, after the end of the starburst, is only 15–20 km s$^{-1}$, while the median velocity width produced by multiple clumps of approximately the same or lower mass in cosmological model M1 with inefficient feedback in Razoumov et al. (2008) is $\sim 44$ km s$^{-1}$. In other words, while the study of winds in isolated clumps might shed some light on the physical conditions in the ISM, the observed velocity dispersion in DLAs comes from a combination of winds and random motions of multiple protogalactic clumps along the line of sight which can only be reconstructed in fully cosmological simulations.

Similar to other multiphase disk models, we find that the cold component of the ISM is distributed in a complex network of filamentary structures confined by hot bubbles and voids. Inside these filaments dense clouds form as gravitational instabilities the growth of which is assisted by the external pressure. Once their growth begins, the clouds proceed to form stars very quickly. Only a small fraction of each cloud ($\sim 1\%$–$2\%$ by mass) is converted into stars, as the clouds are being continuously destroyed by stellar winds from inside, interaction with shells pushed by rapidly expanding nearby hot bubbles, and collisions with other clouds. In our simulation, clouds are transient objects constantly exchanging mass and energy with the cold shells and filaments, as well as with the hot gas, and rarely surviving as discrete entities for longer than a fraction of the rotational period.

The reduced cold gas fraction in the 1/10 solar metallicity model which is more representative of DLA metallicities at $z = 3$ resulted in a slightly delayed SF. However, lower cooling had little overall effect on the ability of the disk to develop a complex multiphase ISM. A large volume filling fraction of the hot gas near the galactic midplane produced large-scale outflows similar to the ones seen in the solar metallicity run.

In this paper, we chose the typical clump masses and initial conditions representative of protogalactic environments at $z = 3$. We expect similar winds to arise in grid-based cosmological simulations at $\sim 10$ pc spatial resolution. Although none of the current cosmological models have such resolution, we argue that using AMR techniques to zoom in on those protogalactic clumps that have a high gas infall rate will allow us to obtain galactic winds from thermal feedback in the cosmological context, without suppressing cooling or using kinetic feedback.

I thank Jesper Sommer-Larsen and Eduard Vorobyov for many enlightening discussions, and the referee Fabio Governato for many useful comments on the original manuscript. I am grateful to Marc Schartmann for providing me with the cooling data. Computational facilities for this work were provided by ACEnet, the regional high performance computing consortium for universities in Atlantic Canada. ACEnet is funded by the Canada Foundation for Innovation (CFI), the Atlantic Canada Opportunities Agency (ACOA), and the provinces of Newfoundland & Labrador, Nova Scotia, and New Brunswick. I acknowledge financial support from ACEnet.

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