THE NATURE AND ORIGIN OF THE NONVOID Lyα CLOUD POPULATION

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Received 2002 November 7; accepted 2003 June 4

ABSTRACT

I continue my study of the low-redshift Lyα cloud population. Previous work showed how galaxy catalogs could be used to attribute relative degrees of isolation to low-redshift Lyα clouds found in Hubble Space Telescope–Goddard High Resolution Spectrograph spectra. This enabled the separation of clouds into two distinct populations corresponding to two distinct environments, variously characterized as void/unshocked and nonvoid/shocked. Void clouds have a steep cumulative equivalent width distribution (i.e., many smaller absorbers), while nonvoid clouds have a flat distribution. I show that N-body/hydro simulations of Lyα clouds are inconsistent with observations of the clouds as a function of their environments. Simulations fail to predict the existence of significant numbers of detectable void clouds and incorrectly predict the characteristics of nonvoid clouds. Implicated in this failure is the so-called fluctuating Gunn-Peterson approximation (FGPA), which envisions that Lyα absorbers are formed in the large-scale structures of coalescing matter. A recent paper (of mine) has modeled the void cloud population as subgalactic perturbations that have expanded in response to reionization. It is notable that success in this modeling was contingent on using the more massive isothermal halo in place of the standard Navarro, Frenk, & White halo, for it was found that gravitational restraint on evaporation of baryons is key to producing detectable void absorbers. In this paper I extend my modeling of Lyα clouds to nonvoid clouds, using the same basic cloud model. In the case of voids, clouds are in a quiescent environment, while nonvoid clouds are thought of as void clouds that have accreted to the denser, turbulent intergalactic medium surrounding galaxies and are thus subjected to bow shock stripping. Model void clouds are analytically shock-stripped, and a column density spectrum (CDS) is derived, based on the same halo velocity distribution function as that used to explain the void CDS. The nonvoid CDS produced by shocked subgalactic clouds are found to be capable of producing an excellent fit to the observed nonvoid CDS without recourse to the FGPA mechanism.

Subject headings: dark matter — intergalactic medium — large-scale structure of universe — quasars: absorption lines

1. INTRODUCTION

N-body simulations now occupy a prominent position in the field of astrophysics. Their results promulgate a picture of structure formation with which it is hard to argue. The reason for this is that, through a variety of means, simulations have been designed to be consistent with high-redshift Lyα forest spectra, and they are integrated into the body of what can only be termed the standard model. However, because of the way cloud simulations are compounded, the results at high redshift can hardly be cited as proof of the accuracy of their simulations—only of their self-consistency.

Recent simulations of Lyα clouds by Davé & Tripp (2001) have extended predictions of models down to a redshift of zero. On the basis of their simulations, they predict a column density spectrum (CDS) with a steep cumulative spectral slope, \( S_{\text{cum}} = -1.15 \pm 0.04 \). Simulations generally show that Lyα forest absorbers arise from the mildly over-dense, highly photoionized gas that traces the dark matter (DM) potentials of large-scale structures surrounding galaxy concentrations (Bi 1993; Miralda-Escudé et al. 1996; Weinberg et al. 1997; Croft et al. 1998; Riediger, Petitjean, & Mucket 1998; Davé & Tripp 2001). In this paper, I generally refer to this as the “intergalactic medium” (IGM). This will contrast with the voids, which are not dominated by galaxies. The mechanism for the formation of Lyα clouds in these simulations is the fluctuating Gunn-Peterson approximation (FGPA), as explained in Bi (1993), Weinberg et al. (1997), Croft et al. (1998), and Davé & Tripp (2001). It is based on the assumption that gas is substantially stripped or evaporated from all smaller halos, forming a roughly homogeneous filament surrounding the fully nonlinear coalescing structures. These simulations have never predicted a significant low-redshift population of Lyα clouds in voids; diffuse gaseous structures in voids disperse with the Hubble flow and today would be essentially undetectable (Riediger et al. 1998; Davé et al. 1999).

At low redshift, galaxy redshift catalogs can be used to assess the relative proximity of Lyα clouds to galaxies and their larger structures. By so doing, it will be possible to check on the detailed predictions of the simulations. Therefore, the study of low-z absorbers as a function of environment may provide a crucial test for the N-body/hydro simulations.

In Manning (2002, hereafter Paper I), low-z Lyα absorber data (Penton, Stocke, & Shull 2000) were used, together with galaxy redshift catalogs, to assess the relative isolation of low-redshift Lyα clouds. It was shown how the summed scalar tidal field in space could be calculated, so that the relative isolation of clouds could be evaluated. I used a limiting tidal field \( S_{\text{lim}} \) to divide the cloud catalog into low and high tidal field catalogs. As with Paper I, the tidal field is given in units of inverse Hubble time squared, resulting in a dimensionless parameter on the order of unity. The

1 The CDS, as well as the equivalent width distribution function, is well fitted by a power-law distribution. Thus, the “slope” is the index of the power law.
equivalent width distribution functions (EWDFs) of these catalogs appear to be well fitted by power laws. I use the model \( \log dN(\mathscr{W})/dz = C + \mathcal{W} \log(\mathscr{W})/63 \text{ mA} \), where \( N(\mathscr{W}) \) is the number of clouds per unit redshift with rest equivalent width \( \geq \mathscr{W} \). Results of the fits can be seen in Figure 1B (see figure legend). It was a surprise to find that a large population of clouds exists in extreme isolation. Void clouds have a steep EWDF \((T \approx -1.6)\), while nonvoid clouds have a flatter slope \((T_{NV} \approx -0.5)\). Here and elsewhere I use the subscripts “V” and “NV” to stand for “void” and “nonvoid.” Thus, there exist two separate populations of clouds. The trends of fitting parameters with variations in limiting tide \( T_{\text{lim}} \) show that the two distinct types of clouds are separated by a transition zone \( (\text{vertical dotted lines}) \), whose width is plausibly caused by measurement errors, intrinsic scatter (in the Tully-Fisher relation), peculiar velocities of clouds and galaxies, and the spatial range a cloud travels during its transition from a void-type to a nonvoid-type galaxy. The dichotomy of types that is seen in these data, especially in the difference in slopes between void \( (T \leq T_{\text{lim}}) \) and nonvoid EWDFs \( (T \geq T_{\text{lim}}) \), is dramatic. There exists a similar dichotomy—unshocked versus shocked—found in the simulations of Riediger et al. (1998) and Cen & Ostriker (1999), suggesting that the phenomenology of nonvoid clouds may be explained in terms of shocks.

The cumulative distribution of tidal field strengths \( (T \leq T_{\text{lim}}) \) over the lines of sight from which the cloud data were taken (Penton et al. 2000) is shown in Figure 1A. It is used in conjunction with the range of values of \( T_{\text{lim}} \) in the transition zone (Fig. 1B) to assess the volume filling factor of voids. The center of the transition is taken to be the tidal field contour at which the shocked and unshocked populations meet. At \( z \approx 0 \) the void filling factor can be read off the figure,

\[
\frac{f_V}{V} = \frac{0.86^{+0.05}}{-0.11},
\]

in substantial agreement with the model of Cen & Ostriker (1999; \( \sim 90\% \)). This is the fraction of the universe occupied by void-type clouds—hence, the volume containing unshocked clouds. Void clouds have a steep slope, which according to the analysis of Manning (2003, hereafter Paper II), requires clouds to have flat baryon distributions \((\rho_b \propto r^{-1.5})\), so that the observed absorption systems are detected at relatively large impact parameters (e.g., \( r_p \sim 29 \text{ kpc for } N_{HI} = 10^{13} \text{ cm}^{-2} \)). In the shocked regions surrounding galaxy concentrations, such a diffuse structure would not be possible if significant cloud motions were present. Of course, the logic behind expecting cloud motions is that the gravitational potentials of coalescing large-scale structure are driving them.

Because the N-body/hydro simulations have uniformly predicted that, at least at lower redshifts, \( \text{Ly}\alpha \) absorbers occupy regions in proximity to galaxy concentrations, their predicted CDS spectral slopes should agree with the observations of the local nonvoid clouds, since both are referring to clouds in the same locations. Figure 2 is a comparison of predicted and observed spectral slopes. The dashed line represents the slope of the cumulative CDS

\[2\text{ Simulations produce a CDS, while observations produce EWDFs. The blanketing that occurs in clouds that are not optically thin (}N_{HI} \geq 10^{13.5};\text{ Paper II, Fig. 9) results in spectral slopes of CDS being generally flatter than those of the corresponding EWDF.}\]
The goal of the current paper is to explain the nature of nonvoid clouds. I do this in terms of the environment in which they are found. I here describe a theory in which prediction of Davé & Tripp (2001), with an arbitrary normalization. Also shown are CDSs derived from EWDFs according to the method of § 5.3 of Paper II; the heavy line represents the CDS of nonvoid clouds ($\mathcal{S} \geq 0.3$), and the thin line represents the mean CDS. The predicted slope of Davé & Tripp (2001), $\mathcal{S}_{\text{sim}} = 2.5 \pm 0.4$, does not compare well to the observed nonvoid EWDF slope, $\mathcal{S}_{\text{NV}} \approx 0.5 \pm 0.1$ (Paper I, Table 3) and agrees even less with the CDS slope $\approx 0.3$. Analysis shows that void clouds are responsible for the steepness of the mean EWDF at $z \approx 0$; low EW clouds are quite rare in the turbulent IGM, as the cutoff in the nonvoid CDS in the Figure 2 shows. But simulations have “detected” low-column density clouds in the IGM where observations suggest that their detection would be very difficult. This suggests that the analysis of Doppler parameters in standard N-body/hydro simulations is incorrect. I address this problem in more detail in § 4.

The need to explain the void clouds, even while the standard model predicts no significant numbers, drives one to reconsider the predictions of the FGPA (Bi 1993; Weinberg et al. 1997; Croft et al. 1998; Davé & Tripp 2001). But § 2 of Paper II clearly showed that the predicted Doppler parameters for clouds in voids produced by this scenario exceed by far the observed $b$-values of void clouds from Hubble Space Telescope–Goddard High Resolution Spectrograph spectra (Penton et al. 2000). Void clouds have Doppler parameters roughly half those of nonvoid clouds (Paper I). Clearly, this shows that void clouds cannot be expanding with the Hubble flow. If they are not produced by a fluctuating Gunn-Peterson effect, then how else does one explain void clouds except as discrete—i.e., as subgalactic structures, remnant survivors from the reionization epoch?

In Paper II void Ly$\alpha$ clouds were modeled as gas associated with subgalactic halos that has responded to the epoch of reionization by evaporating from the halos, albeit at a gravitationally restrained rate. A one-dimensional Lagrangian hydro code (Thoul & Weinberg 1995) was used to track the evolution of the baryons following reionization at high resolution down to a redshift $z = 0$. The products of these simulations are used to calculate model CDSs. Two different untruncated halo models are used, the Navarro, Frenk, & White (NFW; 1996, 1997) halo and an isothermal mass distribution ($\rho \propto r^{-2}$).

The NFW halo is the outcome of numerical simulations, and it would seem to be the first choice for a model. However, in the analysis of Paper II, the NFW halo failed to restrain the evaporation of baryons sufficiently to produce measurable column densities in a void environment at $z = 0$. However, the isothermal halo proved viable as long as the distribution of cloud halo circular velocities was steep, consistent with that derived by Klypin et al. (1999) and Klypin (2002) for isolated halos (see Paper II, § 6.2).

According to N-body simulations, an isolated galaxy should have a mass distribution in agreement with that of the NFW halo, a steep $r^{-2}$ density profile for $r > r_{\text{vir}}$. However, this conjecture is inconsistent with the findings that satellite galaxy distributions in groups and clusters follow an approximately inverse square number density relation with radius far beyond $R_{\text{vir}}$ or $R_{\text{eff}}$ (Seldner & Peebles 1977; McKay et al. 2002) and have velocity dispersions that are flat to similar distances (Zaritsky & White 1994; Zaritsky et al. 1997; Zabludoff & Mulchaey 2000; McKay et al. 2002). These results are indicative of an isothermal, rather than an NFW mass distribution.

Recent rethinking of the McKay et al. (2002) results (Prada et al. 2003) suggests that the above results are affected by interloper galaxies that are randomly distributed in space (hence, in velocity or redshift). However, that small galaxies are relatively unclustered does not imply that they are randomly distributed: their conjecture is in strong contrast with findings that satellites have a number distribution $n \propto r^{-2}$ (McKay et al. 2002) around their primaries. Prada et al. claim also to have found a method to detect interlopers placed into simulated data that can then be applied to real data. It is odd that although interlopers are to be randomly inserted, their Figure 3 shows a distinctly nonrandom distribution of interlopers. One wonders whether the algorithm for identifying interlopers has been applied in a way that picks out things inconsistent with the halo model. These doubts prompt the question of whether they merely “discovered” what they had presumed at the outset. This issue remains to be fully resolved, but for the present, I consider the original work (McKay et al. 2002) to be plausible and probably correct in its essentials. In support of this are two points. First, this assumption is at least consistent with the results of Paper II that NFW halos were not good cloud models and that isothermal halos are. Second, this particular assumption regarding the outer regions of galactic halos is not essential to the analysis, but it will be seen that it is consistent with other data to be developed in § 4.3.

This same isothermal model is the basis of a successful explanation of the void EWDF. Perhaps nonvoid clouds may be explained by a similar approach.

Fig. 2.—CDS of the nonvoid clouds (heavy line for $\mathcal{S} \geq 0.3$), shown in comparison to the mean CDS (light line). The dashed line represents the slope of the CDS predicted by Davé & Tripp (2001) for clouds that are expected to be found in regions of high tidal field. The nonvoid CDS has been adjusted to represent its line density to the CDS averaged over all space. Over nonvoid space, the nonvoid CDS has a $\approx 7$ times larger line density.
nonvoid clouds are produced by discrete clouds. At the epoch of their formation, subgalactic halos must have been distributed fairly evenly in the universe—approximately half in mildly overdense regions and the other half in mildly underdense regions. As the universe evolved, the halos in overdense regions must be carried with the flow into the growing zones of shocked gas, as visual presentations of structure formation convincingly show. Thus, according to Birkhoff’s theorem (Birkhoff 1923), underdense regions came to have a locally higher Hubble constant, which tends to promote the deepening of the underdensity, dispersing their halos and suppressing hierarchical growth. Of the halos that are now in nonvoid space, many may have arrived during the primary and secondary infall of the coalescing large-scale structure. At later times, when voids are well established, the “gravitational repulsion” (Piran 1997) of the contents of voids requires that void clouds will be ejected at velocities dependent on void sizes and the values of the expansion parameter in the void.

Thus, the above reasoning strongly suggests that the great majority of current nonvoid clouds were, at one time or another, standard unshocked void clouds. Hence, nonvoid clouds can be characterized with roughly the same halo velocity distribution function (HVDF) as derived for void clouds (Paper II), although the normalization will be different (see below).

The effect of the accretion of delicate void clouds to the shocked nonvoid space must be dramatic. When the cloud encounters the dissipated gas in nonvoid space, the tenuously held gas is shock-stripped, truncating the cloud and resulting in a modification of its EWDF. It is these effects that I intend to follow in this paper. The goal is to see if void clouds (i.e., as subgalactic structures), transformed by plausible shocks in the intergalactic medium, can be used to explain the nonvoid EWDF at low redshift.

The cosmology assumed in this paper is that of Papers I and II—a standard flat $\Lambda$ model with $h = 0.75$. The total matter density of voids is referred to as either $\Omega_{V}/\Omega_{m}$ or $\Omega_{V}/\Omega_{m}$, where $\Omega_{m} = 0.3$ is assumed. As in the other papers in this series, I assume that the cosmic baryon density is $\Omega_{b}/\Omega_{m} = 0.1$. Recent results from the Wilkinson Microwave Anisotropy Probe (WMAP; Spergel 2003) suggest a substantially larger value, $\Omega_{b}/\Omega_{m} = 0.166$. The effects of the larger value will be noted. The large discovered line density and small Doppler parameters of void clouds (Papers I and II) strongly suggest that they are to a significant degree self-gravitating and discrete. I treat them as such herein.

I begin the analysis in § 2 by studying the effects of shocks on model void clouds as a function of their velocity relative to the IGM. The nonvoid column density spectrum is modeled in § 3. In § 4 I discuss some of the broader issues touched upon in this paper, and I summarize my findings in § 5.

2. CONSTRAINING CLOUD VELOCITY

I model all Ly$\alpha$ absorbers as initially taking the form of void clouds and therefore consistent with the models produced in Paper II. I view the difference in slopes between nonvoid and void EWDFs as attributable to the relatively extreme conditions of the IGM—a denser, hotter, and turbulent environment. I propose that the primary factor in the modification of cloud characteristics is ram pressure from the relative motions of clouds through the IGM.

To constrain the rate of motion in the IGM to which clouds are subjected, I model the effects of shocks produced by clouds moving at a range of velocities within a medium of density $\rho_{NV}$. What ram pressure will explain the change in shape and relative normalization of the CDS? As noted above, this methodology assumes that the transition from void to nonvoid cloud characteristics is currently brought about by the impact of the clouds with the dissipated gas near the $\mathcal{T} = 0.1$ contour.

2.1. Shock Stripping of Void Clouds

Murakami & Ikeuchi (1994, hereafter MI94) probed the effects of the stripping action of blast waves on minihalos. Minihalos (see, e.g., Rees 1986) were once utilized to explain the Ly$\alpha$ forest (Rees 1986; Murakami & Ikeuchi 1993) and are closely related to those subgalactic halos studied in the present work. MI94 envisioned two phases of stripping—the first being the immediate result of the onset of the shock and the second being the gradual stripping of the remnant by the relative velocity through the medium. MI94 found that the isothermal minihalos suffer significant erosion during the initial shock only where the internal pressure of the cloud is less than the ram pressure. For the case of a cloud with velocity $v_{c}$ encountering a dissipated medium with gas of density $\rho_{g}$, the ram pressure on the cloud is

$$p_{\text{ram}} \equiv \rho_{g} v_{c}^2. \quad (2)$$

MI94 showed that minihalos could withstand the secondary stripping for a sustained amount of time if the escape velocity from the cloud were in excess of the oblique flow within the shock. Some clouds were seen to survive in excess of 3 Gyr.

The initial cloud models are produced according to the methods explained in § 6 of Paper II. In these simulations, 200 baryonic bins are used. The first strip, which removes gas at pressures less than the ram pressure, can be implemented by the following transformation of density in each Lagrangian bin,

$$\rho(i) \rightarrow \rho(i)e^{-p_{\text{ram}}(\rho(i))}, \quad (3)$$

where the pressure in the cloud in the $i$th bin is $p(i)$. This formulation produces a fairly abrupt truncation of the baryon density when the cloud pressure is less than the ram pressure. It is assumed that the density of gas in the nonvoid medium (see eq. [2]) is

$$\rho_{NV} \approx 2 \Omega_{b}/\Omega_{m} \rho_{\text{crit}}, \quad (4)$$

where $\rho_{\text{crit}} = 3H^2/(8\pi G)$, a function of redshift. This value is in recognition of the fact that this region is undergoing a mildly nonlinear collapse, and therefore the average density should be mildly supercritical—i.e., $\sim 2\rho_{\text{crit}}$.

In Figure 3 I show the results of subjecting unstripped model clouds (top line in each panel) to ram pressures of a gas of the above density and outfall velocities 25, 50, 100, and 200 km s$^{-1}$.

2.2. Bow Shock Stripping

When the cloud outfall velocity is greater than the sound speed of the ambient medium, a bow shock will result. I assume that the IGM has an average temperature $T_{NV} = 10^{4}$ K, consistent with an adiabatic sound speed of
the cloud is totally stripped even at the density (critical velocity)
dotted line represents the hydrogen density in the background (critical
description of eq. (3) for various velocities \(v_c\) for various velocities
\(v_c\) survive larger ram pressures. In the final panel, the cross section of the
\(v_c = 30 \text{ km s}^{-1}\) cloud when \(v_{cl} = 200 \text{ km s}^{-1}\) is only about \(\frac{1}{4}\) of that when
\(v_{cl} = 100 \text{ km s}^{-1}\).

c_s \sim 17 \text{ km s}^{-1}. \) This temperature is consistent with the simulation
of Davé & Tripp (2001) for an overdensity \(\sim 4/\rho_{\text{crit}}\).
In sustaining the first shock, the cloud has been stripped
down to a volume within that the pressure is greater than
the ram pressure of the shock. From this point, a quasi-stable situation results; a bow shock is set up that stands off
some distance from the cloud proper. The ambient gas
penetrates the shock and is compressed and heated, according to
the Rankine-Hugoniot jump conditions, producing a shear
layer that meets with the cooler, denser medium of the
cloud. There is a high-pressure zone at the head of the cloud,
owing to the presence of the moving cloud immediately behind it, causing gas to be diverted around it. Gas is then
accelerated down the flanks of the cloud by the pressure
differential. The transverse motion over the cooler and denser
cloud body may cause Kelvin-Helmholtz (K-H) instabilities
that could strip away the cloud, layer by layer.

For plane shocks in the Mach range of \(3 \leq \mathcal{M} \leq 6 \) (\(50–100 \text{ km s}^{-1}\)), the velocity inside a plane shock has Mach numbers ranging from \(0.49\) to \(0.46\). Oblique shocks produce higher Mach values inside the shock. This fact, plus the pressure gradient along the length of the cloud inside the bow shock, means that the velocity transverse to the cloud may substantially exceed Mach 0.5, perhaps by a factor of 1.5 or so. At the same time, the contrast between the average cloud density in the unstripped part of the cloud and the gas
between the cloud and the bow shock varies from \(\sim 50\) to \(64\) to \(90\) for \(v_{cl} = 50, 75,\) and \(100 \text{ km s}^{-1}\), respectively. According
to the one-dimensional analysis of Vietri, Ferrara, & Miniati (1997), the growth rate of K-H perturbations at \(0.7 \leq \mathcal{M} < 1.0\) is essentially zero for adiabatic fluids when

the density contrast between the cloud and the stripping medium is on the order of 100. These considerations suggest
that stripping rates are low for the outfall velocities we are
considering.

Anecdotal evidence also suggests that clouds may endure
the stripping of the diffuse IGM gas for long periods without
significant mass erosion. For instance, the very existence of the Local Group compact high-velocity cloud (CHVC) 125+41–207 at a distance \(50 \text{kpc} \lesssim d \lesssim 137 \text{kpc}\) (Brüns, Kerp, & Pagels 2001), with its dense core and a long tail,
strongly suggests that it has survived billions of years of
stripping. Since CHVCs are found to have an average velocity \(\sim 100 \text{ km s}^{-1}\) relative to the barycenter of the Local
Group (Braun & Burton 1999), this cloud would have to
have existed for up to \(\sim 10 \text{ Gyr}\) in order to have moved a Local Group diameter of \(1 \text{ Mpc}\). Since there is no conceiv-
able way of creating this cloud within the Local Group in recent
times, we must conclude that it has been traveling through
the IGM at a similar velocity for a time on the order of
\(10 \text{ Gyr}\), retaining much of its mass. Thus, this and other
CHVCs may be ancient objects that have survived billions
of years of bow shock stripping; they could be the dissipa-
tively stripped and compacted ancestors of secondary infall,
as explained in the scenario of Manning (1999).

While it is reasonable to postulate that smaller clouds
might not endure this stripping as long as larger clouds,
there is no way at present, short of detailed hydro/gravity
simulations, to precisely determine the lifetimes of clouds
under bow shock stripping. However, we may assume that
they all survive on the order of \(10 \text{ Gyr}\), understanding that
this may overestimate the quantity of surviving clouds in
nonvoid space, at the present time. However, since clouds
with low halo velocities are stripped much more efficiently
by shocks, large clouds dominate the cross section of absorbers at the velocities relevant in this problem, so that
small clouds will have only a small effect on results in any
case.

2.3. Turbulent Mixing of the Surviving Cloud

In the globular cluster formation model of Manning
(1999), the internal baryonic density of self-gravitating clouds that are stably responding to supersonic winds (i.e.,
clouds that are large enough to survive both stages of strip-
ing) must increase with time. This is partly due to the decel-
eration of the cloud by ram pressure but is also the result of a cycle of pressure-heating at the front end of the cloud, and
radiative cooling, as the denser cloud gas is pushed along
toward the trailing end of the cloud by the shear wind. The
K-H instabilities may gradually introduce an orderly, toroi-
dal convection pattern in the cloud. This physical picture
may be very similar for void clouds entering the nonvoid
environment. The effect of both cloud deceleration (includ-
ing a displacement of the baryonic cloud from its dark halo)
and the fluid waves driven down the “fetch” of the cloud’s
edge is to disrupt the previous density profile within the
truncation radius of the shock. In the simulations of MP94,
the central condensation of the baryons within the bow
shock is quickly lost. There are thus good grounds for
assuming that the baryons within the shock (except in the
shear layer in between) become more evenly distributed;
cloud containment switches from gravitational to pressure
constraint when moving into nonvoid space.
This general picture is confirmed by Figure 2 of M194; by the time of Figure 2d, \( \sim 1.7 \) Gyr after the initial shock, a shear layer envelops a cloud with a flat density profile, bounded by sharp density gradients. The loss of the central condensation of this model cloud was accomplished in about one-half the time estimated above.

It is thus expected that the clouds in “undisputed” nonvoid space (i.e., \( \log F \approx -0.7 \), outside the transition zone) will approximate a flattened or random mass distribution inside the shear layer of the cloud, so that the average density in random sight lines is independent of the cloud impact parameter. In the transition zone, one may find both void clouds and clouds in various stages of the process of being transformed into nonvoid clouds.

To account for this effect in model clouds, I redistribute the mass within the truncated cloud so that the density is uniform, but I apply the same exponential factor used in equation (3) to smooth the edges. In addition, the neutral fraction of hydrogen in the cloud must be “flattened” as well; I substitute the mass-weighted neutral fraction within the truncated cloud summed over each bin in the truncated cloud. Figure 4 shows the density profiles derived using this methodology for various outfall velocities \( v_{\text{cl}} \). The halo velocities corresponding to the various lines in the figure are given by

\[
v_c = 5.31 \times 10^{0.05v} \text{ km s}^{-1},
\]

where \( n = 16 \) (i.e., 33.5 km s\(^{-1}\)) for the far right-hand side line, \( n = 15 \) for the next at 29.9 km s\(^{-1}\), then 26.6, 23.7, 21.1 km s\(^{-1}\), etc.

3. MODELING THE NONVOID CDS

The CDS is produced using a method very similar to that used to model the void clouds and the HVDF to produce the void CDS (Paper II, § 6). The difference in treatment is that there is an extra variable—the cloud velocity \( v_{\text{cl}} \) that results in the stripping of clouds. Each model CDS is initially normalized using \( \Phi_F \), the void luminosity function (LF) normalization, and must be adjusted to approximate the observed CDS with a “concentration factor” \( f_{\text{mult}} \), which is a function of cloud velocity.

The first step in modeling the nonvoid CDS is deciding which density profile of the shocked clouds works best. The upper panel of Figure 5 shows the normalized CDS for a shocked cloud \( (v_{\text{cl}} = 100 \text{ km s}^{-1}) \) in which the density profile is unadjusted, as in Figure 3 (short-dashed line), one in which it is flattened, as in Figure 4 (solid line), and an average of the two profiles (dot-dashed line). This average is produced by simply averaging the number of H atoms in the respective Lagrangian bins of the unflattened and flattened clouds. Note that the range of legitimacy of this gas profile is expected to be confined to the transition zone since clouds are expected to be fully flattened by the time they emerge from it. These CDSs are shown in relation to the observed nonvoid CDS (\( \mathcal{F}_\text{lim} \geq 0.1; \) heavy solid line). For reference, the void CDS is represented by the long-dashed line. The quality of the fit to the CDS is consistently good over the range 75 km s\(^{-1}\) \( \leq v_{\text{cl}} \leq 200 \text{ km s}^{-1}\).

\footnote{In the modeling of Paper II, this is the largest halo to survive without inside-out collapse and star formation.}

For a large cloud, a velocity of 100 km s\(^{-1}\) will truncate the cloud at about 100 kpc (see Fig. 4). I use these values as fiducial in the calculation of the timescale for the transformation from a void cloud to a nonvoid cloud. A useful conversion for the velocity is 100 km s\(^{-1}\) \( \sim 100 \) kpc Gyr\(^{-1}\). Thus, it would take \( \sim 2 \) Gyr for the cloud to pass completely into the dissipated gas of the filaments. During and after the process of shock stripping, the baryonic cloud is being decelerated by the ram pressure. I calculate the time required for the baryonic cloud to be slowed enough for it to become displaced from the DM by 1 cloud radius. DM plays an important role in maintaining the central condensation of the cloud, and when it is gone, pressure gradients can quickly redistribute the gas. The deceleration caused by ram pressure is

\[
a = \frac{\rho_{\text{NV}} \pi (r_{\text{cl}} v_{\text{cl}})^2}{m_{\text{cl}}},
\]

I am interested in when the displacement is 1 cloud radius: \( r_{\text{cl}} = 0.5 a^2 \). Solving,

\[
\tau = \left( \frac{r_{\text{cl}}}{v_{\text{cl}}} \right) \sqrt{\frac{8 \rho_{\text{cl}}}{3 \rho_{\text{NV}}}},
\]

Fiducial values for the density of dissipated gas in the IGM are \( \rho_{\text{NV}} = 2 \Omega_b \rho_{\text{crit}} \) and \( \rho_{\text{cl}} \approx 10 \Omega_b \rho_{\text{crit}} \). Thus, since \( r_{\text{cl}}/v_{\text{cl}} = 1 \) Gyr, \( t \approx 3.6 \) Gyr. In § 4, I show that the characteristic half-width of the transition zone is \( \sim 0.5 \) Mpc (for \( 0.1 \leq \mathcal{F} \leq 0.2 \)). For average cloud baryon densities \( \rho_{\text{cl}} \ll 20 \Omega_b \rho_{\text{crit}} \), the transition timescale \( t \approx 5 \) Gyr. The cloud thus moves less than the half-width of the transition zone by the time it is effectively flattened.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Density profiles resulting from the redistribution of baryons to an average density within the zone where the cloud pressure is greater than the ram pressure, then smoothed at the edge with same exponential used in eq. (3). Shown are the distributions for the range of halo velocities noted in § 2.3, in ascending order, left to right. These profiles provide the fiducial cloud model for the calculation of the nonvoid CDS.}
\end{figure}
These results suggest that the flattened ram pressure–stripped cloud profiles described above produce the best fit to the nonvoid CDS. Thus, results confirm expectations. I therefore adopt the flattened profiles as the preferred non-void cloud model, realizing that it may not work well in the transition zone.

The next step is to constrain $v_{cl}$. The lower panel of Figure 5 shows normalized model CDSs multiplied by the adjustable factor $f_{\text{mult}}$ based on cloud velocities of 50, 100, and 150 km s$^{-1}$, shown in comparison with the observed nonvoid CDS, as derived in Paper I. Note that the high quality of the fit to the observations shown when $v_{cl} = 100$ or 150 km s$^{-1}$ is absent for a velocity as low as 50 km s$^{-1}$.

Figure 6 shows the concentration factors $f_{\text{mult}}$ required to adjust model CDSs, with their void HVDF normalization, to match the observed nonvoid CDS for a range of cloud velocities. Such a concentration factor is the natural result of models of hierarchical clustering (e.g., Lacey & Cole 1993).

It is possible to estimate the value of the concentration factor independently from the relative values of the normalizations of the HVDFs in void and nonvoid space. According to §7 of Paper II, the void CDS can be best explained with the HVDF of the “grown” halo cloud profiles, with slope parameter $\alpha \simeq -1.95$, and with normalization $\phi_{V}^* \simeq 0.06 \phi^*$ (Paper II, §6), where $\phi^*$ is the normalization of the mean LF. With the B-band LF, I use $\phi^* \simeq 0.022 h^3 \text{Mpc}^{-3} = 0.0093 h\Omega_{\Lambda} \text{Mpc}^{-3}$ (Paper II, eq. [36]). Knowing the filling factors, we can write the equation

$$\phi_{V}^* f_V + \phi_{NV}^* f_{NV} = \phi^*,$$

where $\phi_{NV}^*$ is the normalization of the LF in the nonvoid space (again functionally identical to that of the region containing shocked gas), with filling fraction $f_{NV}$, and $f_V$ is given by equation (1) (i.e., $f_{NV} = 1 - f_V$). Thus,

$$\phi_{NV}^* = \phi^* \frac{1 - f_V (\phi_{V}^*/\phi^*)}{f_{NV}} = 6.77^{+1.73}_{-2.95} \phi^* ,$$

where the errors are propagated from the range in $f_V$ in equation (1). Using the void normalization $\phi_{V}^*$ for the grown halos, the expected concentration factor required to arrive
at the normalization of the nonvoid population (eq. [8]) would be

$$f_{\text{mult}} = \frac{\phi_{\text{NV}}}{\phi_{\text{F}}} \approx 113^{+62}_{-49},$$

(9)

although this is subject to a few caveats (see below).

At this point it is convenient to consider how things would appear if I had used $\Omega_b/\Omega_m = 0.16$, consistent with the WMAP data (Spergel 2003), instead of 0.10 ($\S$ 1). I ran the simulations discussed in Paper II using this new value and derived the CDS, which is consistent with the observed void CDS. The fit was managed using the same faint-end slope parameter $\alpha = -1.95$, but the normalization was lower, $f_{\phi} \approx 0.02\phi^* \approx 1/4$ of the value derived with the lower baryon density. These model clouds were analytically shock-stripped as described above, resulting in very similar values of $f_{\text{mult}}$ for a given $v_{\text{cl}}$, apparently the larger cloud neutral fraction, and consequently larger cross section at a given column density, make up for their lower indicative space density in voids when $\Omega_b$ is larger. However, because $\phi^*$ is now lower, equations (8) and (9) have different values. The nonvoid normalization is slightly higher ($\phi_{\text{NV}} = 7.02^{+3.88}_{-3.08}\phi^*$), and the predicted concentration parameter is about 3 times higher ($f_{\text{mult}} \approx 351^{+194}_{-49}$).

Because of the transferral of matter from void to nonvoid space, the distributions of halo velocities of void and nonvoid clouds are causally linked. If the slope of the HVDF does not change going from the unshocked to the shocked environments, and if void clouds are indeed the precursors of nonvoid clouds, then the multiplicative factor needed to adjust the CDSs of stripped clouds to the observed nonvoid CDS is given by equation (9).

However, equation (9) should not be accepted uncritically. Klypin (2002) found that subhalos have HVDFs consistent with a slope parameter $\alpha \approx -1.72$, while isolated halos have $\alpha \approx -1.95$ (see Paper II, $\S$ 6.2). This is suggestive of a flattening of the spectral slope in higher density areas. If the observed nonvoid clouds have average halo circular velocities of $v_c \approx 30$ km s$^{-1}$, then for $\alpha = -1.72$, there would be 2.7 times fewer 30 km s$^{-1}$ clouds in nonvoid space than if $\alpha = -1.95$. This, in turn, would require a reduction of $f_{\text{mult}}$ by a factor of $\sim 2.7$. That is, equation (9) should, by rights, have been $f_{\text{mult}} = \phi_{\text{NV}}(v_c \sim 30)/\phi_{\text{F}}(v_c \sim 30)$, for the greater effect of stripping on small clouds results in the largest clouds providing the bulk of the cross section of stripped clouds. However, we have no direct information on their number density in the IGM, as we do of $\phi^*$ galaxies. Although the higher densities of clouds in nonvoid space gives greater opportunity for hierarchical agglomeration and a consequent flattening of the spectral slope, these clouds are by no means generally subhalos, for the overwhelming majority of nonvoid clouds in this survey are far outside the virial radius of any galaxy (see $\S$ 4).

On the other hand, it is more plausible that $\phi^*$ galaxies, lying in dense zones of the filamentary structures, could have enhanced numbers (relative to the initial, but concentrated, halo spectrum), owing to hierarchical agglomeration of smaller halos—especially of subperturbations accreted during the primary collapse phase at $z \geq 3$. Therefore, I consider it plausible that the $f_{\text{mult}}$ applicable to clouds may be up to $\sim 3$ times smaller than that quoted in equation (9).

Figure 6 shows the trend of $f_{\text{mult}}$ with $v_{\text{cl}}$, neglecting this possible factor. Over the range of velocities of relevance to this study, the concentration factors for the larger baryon density ($\Omega_b/\Omega_m \sim 0.16$) are entirely consistent with those of the smaller baryon density. The inset shows a set of three vertical lines corresponding to the values of $f_{\text{mult}}$ in equation (9) and imply cloud velocities in the range $42$ km s$^{-1} \lesssim v_{\text{cl}} \lesssim 91$ km s$^{-1}$. The dot-dashed line represents the central value of $f_{\text{mult}}$ when $\Omega_b/\Omega_m = 0.16$, implying a central value $v_{\text{cl}} \approx 130$ km s$^{-1}$ and a range $100$ km s$^{-1} \lesssim v_{\text{cl}} \lesssim 150$ km s$^{-1}$.

As noted above, the considerations of hierarchical merging in dense zones suggest that $f_{\text{mult}}$, as calculated by equation (9), may be less than indicated by equation (7) (i.e., 113 and $350$ km s$^{-1}$ for $\Omega_b/\Omega_m = 0.10$ and 0.16, respectively), perhaps by a factor on the order of 3, although the relative isolation of most nonvoid clouds suggests that it is a small fraction of this. According to Figure 6, this would imply a significantly smaller velocity. For $\Omega_b/\Omega_m = 0.10$, this would imply a velocity $v_{\text{cl}} \lesssim 50$ km s$^{-1}$. Recall, however, that the quality of the fit of the model nonvoid CDS to the observed declines when $v_{\text{cl}} \lesssim 75$ km s$^{-1}$. For the larger $\Omega_b$, cloud velocity could be expected to drop from $\sim 130$ to $\gtrsim 80$ km s$^{-1}$ and still give a good fit to the observed CDS slope.

The one thing that may argue against this whole logical construct is, of course, that nonvoid clouds can be understood in terms of an FGPA. I visit this issue in the next section.

4. DISCUSSION AND SUMMARY

Further discussion in three broad areas is needed to tie this investigation together: the FGPA, the transition zone, and the line density of absorbers as a function of $\mathcal{F}$ in nonvoid space.

4.1. FGPA

It was shown in $\S$ 1 that the predictions of the FGPA for the IGM do not appear to agree with observations. The presence of many clouds in void space (Paper I) stands in contrast with their relative absence under the FGPA. Their absorbers are produced in the slowly varying dissipated gas of the filamentary structure surrounding galaxy concentrations. However, the distribution of clouds proponents predict is inconsistent with the observed distribution of clouds in the same nonvoid locale (see Fig. 2). These indicate a significant problem with the standard model of low-$z$ Ly$\alpha$ clouds and hence, by extension, perhaps also with that of the high-$z$ Ly$\alpha$ forest.

Although the present work has shown that nonvoid clouds may be explained by the effects of shocks on previously unshocked void clouds, this does not mean that none of the absorbers have their origin in an FGPA. The above analysis suggests that if they do exist, the FGPA absorber Doppler parameters should be larger than those of subgalactic halos, which are essentially self-gravitating and whose integration path lengths are smaller. Similarly, it appears likely that the prediction of very low column density clouds in the IGM is due to an incorrect assessment of the Doppler parameters. For among the initial assumptions of the FGPA is that of neglecting turbulent effects within the line (which is already broadened by relative velocities on the order of $10^{-40}$ km s$^{-1}$), as explained in Bi (1993). Required integration path lengths are on the order of 1 Mpc at $z \sim 0$ (Paper II). It seems improbable that in a turbulent
medium there would not be a broadening of the spectral absorption lines over distance such as this.

What sources for turbulence might there be? If the Birkhoff effect is propelling centrally condensed clouds into the IGM, this represents a major source of kinetic energy to drive the turbulence. On the high-$T$ side of the nonvoid universe, energy injection comes with superwinds from post-starburst galaxies and the like. If turbulent motions of $\sim 100$ km s$^{-1}$ ($v_{c1}$) exist over scales of 200 kpc (2 $r_{c1}$), then over megaparsec scales, a significant turbulent dispersion of absorption lines on the order of $\geq 100$ km s$^{-1}$ would be plausible. Their Doppler parameters are in fact large enough to make the lines appear as a continuum depression. Since FGPA integration path lengths are weakly correlated with column density, FGPA Doppler parameters should be rather uniformly $\geq 100$ km s$^{-1}$. By contrast, the Doppler parameter histogram of nonvoid clouds finds $b \approx 60$ km s$^{-1}$, with a dispersion of 15 km s$^{-1}$ or so (Paper I, Fig. 7; Paper II, Fig. 15b). These histograms show no sign that there is a higher $b$-component of absorbers. In fact, the 60 km s$^{-1}$ broadening seems appropriate for a centrally condensed cloud undergoing a dissipative interaction with the IGM. Thus, there is no sign of FGPA clouds at $b \leq 100$ km s$^{-1}$, the upper limit for the Penton et al. (2000) data.

4.2. The Transition Zone

Much of the modeling of nonvoid clouds depends on the physical picture of a sudden transition from a cool, diffuse void to a warm, relatively dense, and turbulent IGM. Let us consider this picture in some detail, motivated by the following question: why should nonvoid space have a relatively abrupt end, so that clouds are quickly shock-striped? The fundamental fact about the edge of voids is that, on the one hand, diffuse, adiabatically cooled matter is balanced by a denser and warmer gas on the other. Obviously, the pressure in the latter $\rho_{NV}$ is much greater than that in the former $\rho_{V}$. The pressure difference will cause an expansion of the IGM into the diffuse void gas. Alternatively, the fact that the local expansion parameter in voids is greater than the mean suggests that we may consider that the cool, diffuse gas is flowing into the denser gas at a velocity sufficient to cause stationary shock front. The equation for pressure balance is then

$$\rho_{V}v_{out}^{2} = \rho_{NV} - \rho_{V},$$

(10)

where the “outfall” rate $v_{out} = (H_{V} - H_{0})R_{e}$. Using the relation $v_{out} = (H_{t} - H_{0})R_{e}$, this leads to the finding

$$v_{out} = \sqrt{\frac{k}{\mu_{m} m_{H}} \left( \frac{\rho_{NV} T_{NV}}{\rho_{V}} - T_{V} \right)},$$

(11)

for a stationary shock. The ambient temperature of nonvoid space is assumed to be $10^{4}$ K (see § 2.2), while that of the adiabatically cooled void space is $\sim 3000$ K (see § 4.3 and Fig. 5 of Paper II). We further assume the average gas densities are

$$\bar{\rho}_{V} = 0.1\Omega_{b}\rho_{crit},$$

$$\bar{\rho}_{NV} = 2.0\Omega_{b}\rho_{crit}/\Omega_{m} \rho_{c1},$$

(12)

where the former suggests that the background (unclustered) density of baryons is a tenth of the mean, while the latter is equation (4). Thus, $\rho_{NV}/\rho_{V} \sim 67$ when $\Omega_{m} = 0.3$. These values imply that

$$v_{out} \approx 95 \text{ km s}^{-1}.$$  

(13)

That is, an outfall velocity of $v_{out} \sim 95$ km s$^{-1}$ will maintain a pressure discontinuity consistent with what was presumed here. This accounts for the strong density gradient at the boundary between void and nonvoid spaces and the apparent rapidity of the onset of shock stripping on clouds; it helps confirm the self-consistency of the physical picture.

4.3. The Nonvoid Cloud Spatial Distribution

I now consider what might be learned from the trend of the cumulative line density of Ly$\alpha$ absorbers as a function of $T_{lim}$. The trend in the log of the intercept $C$ in Figure 1B for the nonvoid EWDFs (solid line, right-hand side of subpanel a) appears to be well fitted by a line. I find that the trend is consistent with a cumulative line density at $T_{0} = 63$ mA of $dN(\geq T_{lim})/dT = 78.3T_{lim}^{-1.45}$. The figure shows that this relation is accurate over the range $0.1 \leq T_{lim} \leq 4$. The slope may be taken to give information about the radial distribution of clouds around isolated galaxies, for the steep dependence of tidal field strength with distance from galaxies essentially ensures that high tidal field regions are close to a strong concentration of mass. Consider an isolated, centrally condensed body. It follows that the tide varies as $T \sim R^{-3}$ (Paper I, eq. [17b]), so that the cumulative line density is $dN(\geq T_{lim})/dT \propto R^{1.18}$. The pressure difference will cause an expansion of the IGM into the diffuse void gas. Alternatively, the fact that the local expansion parameter in voids is greater than the mean suggests that we may consider that the cool, diffuse gas is flowing into the denser gas at a velocity sufficient to cause stationary shock front. The equation for pressure balance is then

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Sternberg, McKee, & Wolfire 2002), and with an average Local Group barycentric motion of $-100 \text{ km s}^{-1}$ (Braun & Burton 1999), are representatives of subgalactic halos that accreted to the IGM long ago. They are, I would suggest, the closest examples of the discrete clouds that constitute the nonvoid CDS.

## 5. SUMMARY

A self-consistent picture has been built that uses shock-stripping in the IGM (nonvoid space) to transform void clouds into nonvoid clouds. A connection between the relative LF normalizations of the HVDFs in void and nonvoid space was used to calculate a “concentration factor” that adjusts the CDS of transformed model void clouds for the convergent concentration of clouds into the more compact nonvoid space of the IGM. Whether the concentration factor can successfully explain the observed nonvoid CDS depends on the cloud velocity and the attendant ram pressure stripping. I have shown that nonvoid clouds are consistent with shock-stripped void clouds when this correction factor is employed. When cloud velocities $v_{cl} \gtrsim 75 \text{ km s}^{-1}$, the shape of the model CDS derived here is in excellent agreement with the observations when the baryons in shocked clouds lose their central condensation and become evenly distributed inside the shear layer. Mergers in dense regions of nonvoid space may increase the number density of $L^*$ galaxies, a change that is accompanied by a lowering of the “faint-end” slope parameter $\alpha$. This suggests fewer clouds in nonvoid space (by up to $\approx 2$), lowering $f_{\text{mult}}$, and suggesting lower outfall velocities. For the lower baryon density initially assumed for this and previous papers, the implied velocity could be less than $50 \text{ km s}^{-1}$, but it does not produce a CDS that fits well with observations. However, for the larger baryon density consistent with the WMAP results, $v_{cl} \approx 100 \text{ km s}^{-1}$ appears consistent from the standpoint of the quality of the fit to the observed nonvoid CDS and the implied concentration factor $f_{\text{mult}}$.

Indications from the systematic velocity of CHVCs, and from the requirements of maintaining a strong pressure gradient between void space and the nonvoid environment, appear to require a void “outfall” velocity on the order of $v_{\text{out}} \approx 100 \text{ km s}^{-1}$.

I wish to thank Christopher F. McKee for many helpful comments and suggestions. I thank Hy Spinrad for financial support and for his wisdom during his stint as my research advisor. I received financial support of NSF grant AST-0097163 and the UC Berkeley Department of Astronomy.

### REFERENCES

Bi, H. 1993, ApJ, 405, 479
Birkhoff, G. D. 1923, Relativity and Modern Physics (Cambridge: Harvard Univ. Press)
Blitz, L., Spergel, D. N., Teuben, P. J., Hartmann, D., & Burton, W. B. 1999, ApJ, 514, 818
Braun, R., & Burton, W. B. 1999, A&A, 341, 437
Bri"uns, C., Kerp, J., & Pagels, A. 2001, A&A, 370, L26
Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
Croft, R. A. C., Weinberg, D. H., Katz, N., & Hernquist, L. 1998, ApJ, 495, 44
Davé, R., Hernquist, L., Katz, N., & Weinberg, D. H. 1999, ApJ, 511, 521
Davé, R., & Tripp, T. M. 2001, ApJ, 553, 528
Klypin, A. 2002, in Modern Cosmology, ed. S. Bonometto, V. Gorini, & U. Moschella (Bristol: IOP)
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Lacey, C., & Cole, S. 1993, MNRAS, 262, 627
Manning, C. V. 1999, ApJ, 518, 226
———. 2002, ApJ, 574, 599 (Paper I)
———. 2003, ApJ, 591, 79 (Paper II)
McKay, T. A., et al. 2002, ApJ, 571, L85
Miralda-Escudé, J., Cen, R., Ostriker, J. P., & Rauch, M. 1996, ApJ, 471, 582
Murakami, I., & Ikeuchi, S. 1993, ApJ, 409, 42
———. 1994, ApJ, 420, 68 (M194)
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
———. 1997, ApJ, 490, 493
Penton, S. V., Stocke, J. T., & Shull, J. M. 2000, ApJS, 130, 121
Piran, T. 1997, Gen. Relativ. Gravitation, 29, 1363
Prada, F., et al. 2003, ApJ, submitted (astro-ph/0301360)
Rees, M. J. 1986, MNRAS, 218, 25P
R"odiger, R., Petitjean, P., & Mucket, J. P. 1998, A&A, 329, 30
Seldner, M., & Peebles, P. J. E. 1977, ApJ, 215, 703
Spergel, D. N., et al. 2003, ApJ, submitted (astro-ph/0302209)
Sternberg, A., McKee, C. F., & Wolfire, M. G. 2002, ApJS, 143, 419
Thoul, A. A., & Weinberg, D. H. 1995, ApJ, 442, 480
Tully, R. B., & Pierce, M. J. 2000, ApJ, 533, 744
Vietri, M., Ferrara, A., & Miniati, F. 1997, ApJ, 483, 262
Weinberg, D. H., Hernquist, L., Katz, N., Croft, R., & Miralda-Escudé, J. 1997, in Proc. 13th IAP Colloq., Structure and Evolution of the Intergalactic Medium from QSO Absorption Line System, ed. P. Petitjean & S. Charlot (Gif-Sur-Yvette: Editions Frontières) 133
Zabludoff, A. I., & Mulchaey, J. S. 2000, ApJ, 539, 136
Zaritsky, D., Smith, R., Frenk, C. S., & White, S. D. M. 1997, ApJ, 478, 39
Zaritsky, D., & White, S. D. M. 1994, ApJ, 435, 599