Redshift distribution of Lyα lines and metal systems

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ABSTRACT

The observed redshift distribution of Lyα lines and metal systems is examined in order to discriminate and to trace the evolution of structure elements observed in the galaxy distribution, at small redshifts, and to test the theoretical description of structure evolution. We show that the expected evolution of a filamentary component of structure describes quite well the redshift distribution of metal systems and stronger Lyα lines with log($N_{\text{H}}$) > 14, at $z \leq 3$. The redshift distribution of weaker Lyα lines can be attributed to the population of poorer structure elements (Zel’ dovich pancakes), which were formed at high redshifts from the invisible dark matter and non-luminous baryonic matter, and which at lower redshifts are mainly merged and dispersed.

Key words: surveys – quasars: absorption lines – quasars: general – large-scale structure of Universe.

1 INTRODUCTION

During the last few years essential progress has been achieved both in the observations and interpretations of absorption spectra of quasars. Now a representative set of absorption lines with measured redshifts, column densities and Doppler parameters is available and the main characteristics of absorbers and their evolution are, in general, established (see e.g. Bahcall et al. 1993, 1996; Carswell 1995; Cristiani et al. 1995, 1997; Dinshaw et al. 1995; Hu et al. 1995; Fernandez-Soto et al. 1996; Ulmer 1996; Cooke, Espey & Carswell 1997; Kim et al. 1997). The available information suggests various descriptions of absorbers ranging from pressure-confined gaseous clouds to associations with haloes of galaxies (see discussions in Charltone 1995; Rees 1995; Fernandes-Soto et al. 1996; Miralda-Escude et al. 1996; Petitjean 1997). If at low redshifts a significant number of stronger Lyα lines and metal systems are certainly associated with galaxies (Bergeron, Cristiani & Shaver 1992; Cowie et al. 1995; Lanzetta et al. 1995; Tyler 1995; Le Brune, Bergeron & Boisse 1996), then the population of weaker absorbers, dominating at higher redshifts (Morris et al. 1993; Rees 1995; Fernandes-Soto et al. 1996; Miralda-Escude et al. 1996; Petitjean 1997). If at low redshifts a significant number of stronger Lyα lines and metal systems are certainly associated with galaxies (Bergeron, Cristiani & Shaver 1992; Cowie et al. 1995; Lanzetta et al. 1995; Tyler 1995; Le Brune, Bergeron & Boisse 1996), then the population of weaker absorbers, dominating at higher redshifts, has practically disappeared by the redshift $z \approx 2$, and only some weak Lyα lines are observed far from galaxies even at small redshifts (Morris et al. 1993; Shull 1997).

Now the origin and evolution of absorbers are linked to the process of formation and evolution of high-density structure elements (Petitjean, Mükét & Davies 1995; Hernquist et al. 1996; Miralda-Escude et al. 1996; Zhang et al. 1997, 1998; Theuns et al. 1998, 1999; Weinberg et al. 1998; Bryan et al. 1999; Davé et al. 1999; Machacek et al. 2000). The numerical simulations of the dynamical and thermal evolution of the gaseous component use the same spectrum of initial perturbations that is responsible for the formation of dark matter (DM) and the observed galaxy spatial distributions, and they successfully reproduce the main observed properties of absorbers. This allows us to consider the evolution of absorbers in the context of a more general process of non-linear evolution of small initial perturbations of the DM component and the formation of the observed galaxy distribution, and to compare the theoretical conclusions with the observations.

This approach links the properties of absorbers, at high redshifts, with the spatial galaxy distribution at small redshifts, and allows us to trace some observational characteristics of non-linear evolution of matter distribution up to redshifts $z \sim 3$.

The analysis of large modern redshift surveys, such as the Durham/UKST Galaxy Redshift Survey (Ratcliffe et al. 1996) and the Las Campanas Redshift Survey (Shectman et al. 1996), demonstrates that the galaxy distribution in the Universe can be roughly described as a joint network composed of galaxy filaments and walls. The analysis of both surveys shows that about 50 per cent of galaxies are concentrated in wall-like elements surrounding huge underdense regions with a typical size of 50–100 h$^{-1}$ Mpc (h = $H_0/100$ km s$^{-1}$ Mpc$^{-1}$ is the dimensionless Hubble parameter; Doroshkevich et al. 1996, hereafter LCRS1; Doroshkevich et al. 2000). In many respects such elements are similar to the Great Wall (de Lapparent, Geller & Huchra 1988; Ramella, Geller & Huchra 1992). Galaxy filaments appear between walls and intertwine them into a joint structure. The hierarchy of poorer and sparser filaments – including single galaxies – can be considered as a bridge between the richer and
poorer structure elements formed by the non-luminous baryonic and DM. Such poorer elements contain some fraction of hot gas and could be seen as Lyα absorbers away from galaxies. Observations of weak Lyα absorbers in voids, mentioned above, can be attributed to the poorer DM structure elements.

The evolution of structure elements formed by DM was investigated both theoretically, using the Zel’dovich theory (e.g. Zel’dovich 1970; Zel’dovich & Novikov 1983; Shandarin & Zel’dovich 1989), and numerically (e.g. Shandarin et al. 1995; Cole et al. 1997, 1998; Jenkins et al. 1998; Doroshkevich et al. 1999, hereafter DMRT; Demiański et al. 2000, hereafter DDMT). The statistical description of DM structure evolution for the cold-dark-matter (CDM)-like power spectra was given in Demiański & Doroshkevich (1999, hereafter DD99) and in DDMT. The main simulated characteristics of walls are found to be consistent with theoretical expectations.

Some progress in the theoretical interpretation of properties of absorbers has been recently achieved by Hui, Gnedin & Zhang (1997) and Nath (1997), who used the Zel’dovich approximation for a semi-analytical description of some of the characteristics of the absorbers. Several other theoretical approaches considered were based on the ‘minihalo’ model (Meiksin 1998), the ‘Cosmic Webb’ theory (Bond & Wadsley 1997) and the Press–Schechter method (Valageas, Schaeffer & Silk 1999).

In this paper we examine the observed redshift distribution of absorbers using the available information about the structure parameters at small redshifts (LCRS1; DMRT; Doroshkevich et al. 2000), and the statistical description of DM structure evolution (DD99; DDMT) in models with CDM-like power spectra. We assume that the Lyα clouds trace the potential wells formed by DM pancakes, filaments and walls. This assumption was widely discussed previously (Ikeuchi & Ostriker 1986; Rees 1986; Bond, Szalay & Silk 1988; Miralda-Escude & Rees 1993; Meiksin 1998; Bond & Wadsley 1997; Hui et al. 1997; Nath 1997; Valageas et al. 1999), and it is qualitatively consistent with the results of numerical simulations (Petitjean et al. 1995; Hernquist et al. 1996; Petitjean 1997; Theuns et al. 1998; Weinberg et al. 1998; Davè et al. 1999).

The potential of this approach is limited because of the small number of observed absorbers and because the characteristics of the structure derived from observations are not sufficiently accurately known. The theoretical description of DM structure evolution is also not complete. In particular, it cannot yet adequately describe the important process of the disruption of structure elements and their transformation into a system of high-density clumps. This process depends on many factors (Doroshkevich 1980; Vishniac 1983; Valinia et al. 1997) and strongly influences the observed properties of absorbers both at large and small redshifts (Miralda-Escude et al. 1996; DMRT; DDMT). Moreover, the evolution of DM structure elements and observed absorbers is not identical.

None the less, the limited information allows us to obtain a reasonable description and interpretation of some of the observed characteristics of absorbers. In this paper we consider the statistical description of the redshift distribution of absorbers and metal systems, which is more detailed, in some respects, than that usually used. The comparison of the measured redshift distributions with approximate theoretical expectations (DD99) allows us to statistically discriminate between the contributions of high density filamentary and lower density sheet-like structure elements formed by the DM and gaseous components of matter, and to trace their evolution. These two components of structure elements can be roughly identified with two subpopulations of absorbers discussed, for example, in Bahcall et al. (1996) and Weymann et al. (1998).

This division of structure elements into filaments and more sheet-like walls and pancakes is inevitably statistical only. The more detailed analysis of DM and galaxy distribution, at small redshifts (DMRT; DDMT), demonstrates the limitations of such a description and shows that usually the morphology of structure elements can be more accurately characterized in terms of the degree of filamentarity and/or sheetness alone. The investigation of the morphology and spatial distribution of DM and gaseous structure elements in simulations at high redshifts with the new powerful techniques (such as the minimal spanning tree or Minkowski functional techniques), as well as the direct comparison of morphological and other characteristics of the structure elements with their redshift distribution, is required to clarify this problem and to obtain a more detailed comparison of the observed and simulated matter distributions.

This paper is organized as follows. The theoretical model of structure evolution and the techniques necessary for the analysis are briefly described in Section 2. Section 3 contains information about the observational data bases used. The results of the statistical analysis are presented in Section 4, and discussion and conclusions can be found in Section 5.

## 2 THE REDSHIFT DISTRIBUTION OF ABSORBERS

### 2.1 Pancakes, filaments and walls associated with absorbers

The redshift distribution of absorbers can be characterized by the mean comoving free path between absorbers (l) (Sargent et al. 1980):

$$dN(z) = \langle l \rangle^{-1} c dz / H(z),$$

(2.1)

where

$$H(z) = H_0 \sqrt{\Omega_m (1 + z)^3 + (1 - \Omega_m - \Omega_\Lambda)(1 + z)^2 + \Omega_\Lambda},$$

and

$$dN(z) = n_{abs} \left( \frac{c}{H_0} \right) \frac{H(z)}{dN(z)},$$

where the three terms in equation (2.2) correspond to three main types of structure elements observed at small redshifts: the rich walls (nw), filaments (nφ), formed by galaxies, and poor pancakes (npan), situated far from the observed galaxies.

Such division of structure elements into three different subpopulations is performed for the sake of simplicity only. In particular, there is an anisotropic sheet-like low-density halo around all filaments that are, in turn, later strongly disrupted into a system of high-density clumps. The higher density ridges often

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cross the low-mass pancakes. Walls are also often formed by a system of high-density clumps and filaments connected by lower density bridges. This means that in nature, there is really only one population of structure elements with a broad variety of continuously distributed properties, and these elements can be considered as the more typical and conspicuous ones. None the less, the considered classification makes this analysis simpler and more transparent, as the rate of structure evolution depends upon the degree of filamentarity or sheetness.

2.2 Evolution of DM structure elements

In the DM-dominated Universe the basic characteristics of matter distribution are determined by the process of the formation and evolution of DM structure elements. The observed characteristics of absorbers and the parameters of DM structure elements are not identical, but they are closely connected and relations between these parameters can emerge from suitable investigations.

For the CDM-like transfer function (Bardeen et al. 1986) and the Harrison–Zel’dovich initial power spectrum the approximate statistical description of the formation and evolution of DM structure elements based on the statistics of initial perturbations was obtained in DD99. The random formation and merging of Zel’dovich pancakes with ‘mass’ (the column density of a pancake) \( m \), and their evolution as a result of transversal expansion or compression, are described by approximate expressions similar to the Press–Schechter relations. Similar approximate relations can also be written for the filamentary component of the structure. Here we will apply some of these results to describe the observed evolution of the absorbers.

As is usual in the Zel’dovich theory, the redshift dependence of all characteristics of structure is expressed through a function \( B(\Omega_m, z) \), which describes the growth of perturbations in the linear theory. For the flat universe with \( \Omega_m + \Omega_\Lambda = 1 \), and \( \Omega_m \gg 0.1 \), the function \( B(z) \) can be approximated (DD99) with a precision better than 10 per cent by the expression

\[
B(z)^{-3} = \frac{1 - \Omega_m + 2.2 \Omega_m (1 + z)^3}{1 + 1.2 \Omega_m},
\]

and for an open universe with \( 0.1 \leqslant \Omega_m \leqslant 1 \) and \( \Omega_\Lambda = 0 \) as

\[
B(z)^{-1} = \frac{1 + 2.5 \Omega_m}{1 + 1.5 \Omega_m z}.
\]

(Zel’dovich & Novikov 1983). For \( \Omega_m = 1 \) and \( \Omega_\Lambda = 0 \) both expressions give \( B^{-1}(z) = 1 + z \).

2.2.1 Formation and evolution of DM structure

The evolution of DM structure can be outlined as a progressive matter concentration within more and more massive structure elements, which can be roughly discriminated into pancakes, filaments and walls. The structure elements are primarily formed as Zel’dovich pancakes (Shandarin et al. 1995), but are later successively transformed into filaments and/or (elliptical) clouds. At high redshifts, \( z \gg 5–7 \), a significant fraction of matter (~80 per cent) can be compressed into low-mass pancakes with \( M_3 \sim 10^7–10^8 M_\odot \). Later, some of such clouds can evolve into dwarf galaxies and some could disperse, but the main fraction will be accumulated by more massive structure elements. Properties of the surviving and relaxed clouds can be similar to those discussed in the ‘minihalo’ model (Miralda-Escude & Rees 1993; Meiksin 1994; Rees 1986, 1995).

The filamentary component of structure also forms at high redshifts as a result of the compression of some parts of the pancakes and, at \( z \sim 1–3 \), it is probably the most conspicuous population of high-overdensity structure elements and accumulates 40–50 per cent of DM particles (see e.g. Governato et al. 1998; Jenkins et al. 1998). Further evolution of the structure can be described as a successive merging of lower mass pancakes and filaments into more and more massive wall-like structure elements. The largest observed wall-like elements, similar to the Great Wall, are formed at redshifts \( z \leqslant 1 \) as a result of the infall and intermixture of smaller pancakes and filaments.

In observations, at \( z \leqslant 1 \), galaxy filaments are usually situated within extended underdense regions surrounded by higher density walls, and they form an irregular broken network. This network can be described as a trunk, which is the longest filament of the complex, and a set of shorter branches. This means that the spatial distribution of filaments can be conveniently characterized by the mean 2D surface number density \( \sigma_r(z) \), which is the mean number of filaments intersecting a unit area of arbitrary orientation. For observed galaxy filaments it is estimated as \( \sigma_r(0) = (0.7-1) \times 10^{-2} h^2 \text{Mpc}^{-2} \) (LCRS1). The spatial distribution of observed walls can be characterized by their mean separation \( \langle D_\nu \rangle \) and by their linear density \( \sigma_w \), which is the mean number of walls intersecting a unit length of a random straight line. For the observed galaxy walls it is estimated as \( \langle D_\nu \rangle \approx 40–60 h^{-1} \text{Mpc} \), which corresponds to \( \sigma_w = 2.5–1.6 \times 10^{-2} h^{-1} \text{Mpc}^{-1} \). The low-mass pancakes can be considered as isolated objects and characterized by the mean 3D number density \( v_{\text{pan}}(z) \).

Simulations show that rich pancakes and filaments are relaxed (at least along shorter axes) and are surrounded by an extended DM (and gaseous) halo. Central parts of dense elements are gravitationally confined and are unstable with respect to the small-scale disruption (DDMT). Some of the high-density clumps are usually embedded in filaments and walls, which essentially accelerates the relaxation of the compressed matter. In observations, the effects of such disruptions are seen as groups and clusters of galaxies.

The basic properties of DM structure elements vary in a broad range, but it can be expected that galaxies are formed mainly within richer high-density filaments and pancakes. The essential fraction of poor pancakes and, perhaps, filaments can be invisible, as it does not contain sufficiently bright galaxies. Such structure elements can be observed as weak Ly\( \alpha \) absorbers situated far from any galaxy. A number of such absorbers situated at a distance of up to \( 5 h^{-1} \text{Mpc} \) from the closest galaxy was found by Morris et al. (1993) and Shull (1997).

This description agrees well with results of numerical simulations at small redshifts (DDMT). The validity of this description, when it is applied to structure at high redshifts, is not yet reliably verified with available simulations because of the low density contrast of poor structure elements. The first tests show, however, the existence of three kinds of structure elements, namely high-density filaments and clumps and low-density pancakes in the DM spatial distribution at \( z = 3 \). The theoretical description (DD99) also confirms the self-similar character of structure evolution (at least when the Zel’dovich approximation can be applied). This picture is also qualitatively consistent with other simulations of structure evolution (Miralda-Escude et al. 1996; Governato et al. 1998; Jenkins et al. 1998; Meiksin 1998; Weinberg et al. 1998; DMRT; Davè et al. 1999).
2.2.2 The main factors of structure evolution

The four main factors characterizing the structure evolution are:

(i) the successive formation of structure elements with larger and larger masses;
(ii) the merging of earlier formed, more numerous, low-mass filaments and pancakes;
(iii) the expansion or compression of matter along filaments and pancakes;
(iv) the small-scale clustering of compressed matter and disruption of structure elements.

The action of these factors was discussed in DD99 (Sections 4.1, 4.2 and 5.2) and it was shown that for the CDM-like initial power spectrum and Gaussian initial perturbations it can be approximately described by simple analytical expressions. Some of these relations were tested and confirmed through the direct comparison with DM simulations (DDMT). Here we will briefly summarize these results.

The distribution function of Zel’dovich pancakes with surface density \( m_p \), \( N_p(m_p) \), can be written as follows:

\[
N_p(m_p) \propto \frac{1}{\sqrt{m_p}} \exp\left(-\frac{m_p}{\langle m_p \rangle}\right) \operatorname{erf}\left(\sqrt{\frac{m_p}{\langle m_p \rangle}}\right) \tag{2.4}
\]

and

\[
\langle m_p \rangle \propto B^2,
\]

where the successive merging of low-mass pancakes in the course of the formation of richer pancakes is described by the \( \operatorname{erf} \) function. The process of merging decreases the number density of numerous low-mass structure elements – both filaments and pancakes – with \( m_p \ll \langle m_p \rangle \), but its influence becomes negligible for rare massive wall-like structure elements, with \( m_p \gg \langle m_p \rangle \), and rare rich filaments. For the fraction of pancakes with \( m_{\text{min}} \leq m_p \leq m_{\text{max}} \) from equations (2.4) we obtain

\[
f_p \propto \operatorname{erf}^2\left(\sqrt{\frac{m_{\text{max}}}{\langle m_p \rangle}}\right) - \operatorname{erf}^2\left(\sqrt{\frac{m_{\text{min}}}{\langle m_p \rangle}}\right). \tag{2.5}
\]

For rich walls formed presumably at \( z \approx 1-1.5 \) with \( m_{\text{max}} \rightarrow \infty \) and \( m_{\text{min}} \approx m_w \approx \langle m_p \rangle \) this relation is simplified and we have, approximately,

\[
f_w \propto 1 - \operatorname{erf}^2\left(\sqrt{\frac{m_w}{\langle m_p \rangle}}\right) \propto \operatorname{erf}\left(\sqrt{\frac{m_w}{\langle m_p \rangle}}\right) \tag{2.6}
\]

which constrains the population of massive pancakes. For the subpopulation of poor pancakes, a similar relation

\[
f_w \propto 1 - \operatorname{erf}^2\left(\sqrt{\frac{m_{\text{min}}}{\langle m_p \rangle}}\right) \propto \exp\left(\frac{-m_{\text{min}}}{\langle m_p \rangle}\right)
\]

is valid only at higher redshifts \( z \gg 3.5-4 \) when \( m_{\text{max}} \gg m_{\text{min}} \approx \langle m_p \rangle \), whereas during the most interesting period, \( z \approx 3.5 \) when \( m_{\text{min}} \ll \langle m_p \rangle \), the second term in equation (2.5) can be omitted.

The discrimination between rich walls and poor pancakes seems to be artificial, in some respects, but it allows us to provide a closer connection with the observed galaxy and simulated DM distributions at smaller redshifts. Moreover, rich walls are certainly strongly non-homogeneous and are disrupted into high-density clumps and filaments, which essentially decreases their covering factor. Owing to these peculiarities, such walls can form a special class of objects.

The distribution function of filaments with linear density \( N_f \) and mass \( m_f \) is found to be proportional to

\[
N_f \propto \frac{1}{\langle m_f \rangle} K_0^2 \left(\frac{m_f}{4\langle m_f \rangle}\right) \quad \text{and} \quad \langle m_f \rangle \propto B^4, \tag{2.7}
\]

where \( K_0(x) \) is the modified Bessel function (DD99) and the fraction of rich filaments, with \( m_f \gg \langle m_f \rangle \), is

\[
f_f \propto \exp\left(-\sqrt{\frac{m_f}{\langle m_f \rangle}}\right). \tag{2.8}
\]

As before, the infall of filaments into rich walls decreases the fraction of filaments associated with the network \( \propto \exp\left(\sqrt{m_f/\langle m_f \rangle}\right) \propto B^{-1} \).

Furthermore, the properties of structure are essentially changed as a consequence of matter expansion and/or compression in transversal directions. Compression results in the transformation of the pancakes into filaments and high-density clouds, which decreases their effective surface and also the probability of seeing such a structure element as an absorber. Strong expansion increases the surface of pancakes and the length of filaments and correspondingly decreases their density. In the limiting case, low-mass pancakes and filaments can be transformed into a system of high-density clumps, or they can even completely disperse. The expansion also decreases the column density of \( \text{H}_1 \) below the observational threshold \( N_{\text{H}_1}^{\text{th}} = 10^{12} \text{ cm}^{-2} \), which makes such elements invisible as absorbers. Therefore, the population of structure elements identified with absorbers is restricted by the condition relatively slow expansion or compression in transversal directions. The fraction of such low-mass pancakes decreases with time \( \propto \exp\left(\sqrt{m_p/\langle m_p \rangle}\right) \), and the fraction of such low-mass filaments decreases \( \propto \exp\left(\sqrt{m_f/\langle m_f \rangle}\right) \propto B^{-1} \). The influence of these factors is less important for rare rich walls and filaments.

Owing to the gravitational instability of compressed matter, both pancakes and filaments are usually disrupted into a system of high-density clouds linked by low-density bridges. Such disruption occurs more rapidly in the central high-density parts of structure elements, but its impact is probably not so important for the extended lower density halo. When these processes are taken into account the final relations become very cumbersome and, therefore, a more detailed treatment is not really justified when only a limited set of observed absorbers is available.

When these factors are taken into account we can only approximately describe the expected evolution of the walls, filaments and low-mass pancakes associated with the absorbers. The comoving linear number density of massive walls \( \sigma_w(m) \) with \( m \approx m_w \), the comoving surface number density of filaments \( \sigma_f(m) \) and the comoving number density of pancakes \( \nu_{pan}(m) \), can be approximated by simple expressions:

\[
\sigma_w \propto \exp\left(-\frac{b_w(m)}{B^3}\right), \tag{2.9}
\]

\[
\sigma_f \propto B^{-2} \exp\left(-\frac{b_f(m)}{B^3}\right) \tag{2.10}
\]

and

\[
\nu_{pan} \propto \operatorname{erf}^2\left(\frac{b_1}{B}\right) \left[ \operatorname{erf}^2\left(\frac{b_2}{B}\right) - \operatorname{erf}^2\left(\frac{b_3}{B}\right)\right]. \tag{2.11}
\]

where the parameters \( b_w, b_f, b_1, b_2, b_3(m) \), and the exponential terms in equations (2.9) and (2.10), restrict the formation of structure.
elements with masses \( m \). The term \( B^{-2} \) in equation (2.10) describes the successive infall of filaments into richer walls and the decrease, caused by expansion or compression, of the number of filaments observed as absorbers with \( N_{\mathrm{HI}} \geq N_{\mathrm{HI}}^{\mathrm{thr}} \). The decrease of the number density of pancakes is described by the factor \( b_t \) in equation (2.11).

For the restricted redshift interval \( z \leq 3.5 \), the three-parameter expression for \( r_{\mathrm{pan}} \) can be approximated by a simpler one-parameter expression:

\[
\frac{r_{\mathrm{pan}}}{B^{-1}} \propto B^{-3} \exp \left[ - \frac{b_{\mathrm{pan}}(m)}{B^{-1}} \right],
\]

which correctly describes the asymptotical behaviour of \( r_{\mathrm{pan}} \) at small and large redshifts. In the intermediate region it provides a reasonable precision, \( \sim 10^{-5} \) per cent, for \( z \leq 3.5 \). The more complicated relation (2.11) provides a better description of the evolution of absorbers, especially at higher redshifts \( z \approx 3-3.5 \), and can be used for more refined fitting.

High-density clouds and galaxies are usually embedded in filaments and pancakes and cannot be distinguished as a special class of absorbers. These problems were discussed in greater detail in our other publications DD99, DMRT and DDMT.

2.3 A model of the evolution of absorbers

The relations (2.3) and (2.9)–(2.12) cannot give the full description of the observed redshift distribution of absorbers, but they suggest a possible redshift evolution of various types of absorbers and introduce the function \( B(z, \Omega_{\mathrm{m}}) \) as an important characteristic of such an evolution. It is important that the redshift evolution of free path between walls, filaments and low-mass pancakes is expected to be different, and therefore it might be possible to single out statistically these three subpopulations of absorbers, and to establish correlations between the evolutionary rates and other observational characteristics of absorbers.

The DM structure is quite complicated in itself as it is composed of several types of structure elements with different evolutionary histories. Furthermore, the properties and the evolution of the observed gaseous and DM structure elements are not identical, because additional factors influence the evolution of the gaseous component of the DM-confined structure elements and, therefore, even more complicated evolution of absorbers can be expected. The action of these factors usually decelerates the evolution of the gaseous component but, because of the very low density of this component, its impact on the evolution of the DM component is negligible. Thus, the formation of weak absorbers within ‘minivoids’ is not accompanied by the formation of any DM structure elements (Bi & Davidsen 1997; Zhang et al. 1998; Davé et al. 1999).

The observational restrictions, such as the condition \( N_{\mathrm{HI}} \geq N_{\mathrm{HI}}^{\mathrm{thr}} \), also constrain the population and the observed evolution of the absorbers. Thus, for example, the exponential growth of a fraction of massive high-temperature pancakes (in the limiting case, walls similar to the Great Wall) is not found in the observed distribution of absorbers (Section 4). Moreover, the mean measured \( b \) – a parameter of absorbers related to the gas temperature – remains constant for the observed redshifts \( 2.5 \leq z \leq 3.3 \). This possibly means that some rich DM structure elements have not yet been identified in the absorption spectra of quasars.

The redshift dependence of \( n_{\lambda_{\alpha}} \) is driven both by the evolution of the spatial characteristics of DM structure elements, discussed above, and by the evolution of their covering factor, which characterizes the probability of the formation of an absorption line at the intersection of the line of sight and a structure element. The covering factor depends on local conditions such as, for example, variations of the ultraviolet background and in the activity of the nearest galaxies. Now it can also be described phenomenologically.

The importance of the role of the ultraviolet background was well established after the discussion in Sargent et al. (1980), but the ultraviolet intensity and its possible variation with redshift is only known with a large uncertainty (see e.g. Haardt & Madau 1996; Cook, Espey & Carswell 1997). The influence of systematic variations of ultraviolet radiation is more important at small \( z \) and higher \( z \approx 3-3.5 \) redshifts where the statistic of absorbers is strongly limited. At intermediate redshifts \( 2.5 \leq z \leq 3.5 \), where the main fraction of observed absorbers is situated, the systematic variations of ultraviolet radiation are not so strong, but this radiation is probably responsible for the significant irregular variations in the density of absorbers.

The redshift distribution of observed absorbers can be distorted by the formation of artificial caustics in the redshift space (McGill 1990; Levshakov & Kegel 1996, 1997). As was shown in DDMT, the impact of this effect is certainly small at small redshifts. At intermediate redshifts and for the usually used CDM-like power spectra, the formation of artificial caustics is partly suppressed because of strong matter concentration within the low-mass structure elements discussed in DD99 and Zhang et al. (1998). This factor transforms the continuous matter infall into pancakes into a discontinuous one, increases the density gradient near pancake boundaries and partly prevents the formation of artificial caustics. Moreover, such an artificial caustic is actually the preliminary stage of the formation of a real caustic, and so it is rapidly transformed into a real one. This factor can moderately change the discussed redshift dependence of absorbers.

The contribution of artificial caustics and absorbers within ‘minivoids’, as well as of short-lived rapidly expanding or contracting pancakes, is more important at higher redshifts when weak absorbers dominate. These factors generate an essential noise that is typical for the period preceding the epoch of regular evolution. At such redshifts, the available statistics of observed absorbers are very poor, and our analysis becomes unreliable. Perhaps more detailed and careful investigations based upon the simulations will allow the observational discrimination between this noise and the long-lived structure elements (see e.g. the discussion in Zhang et al. 1998), which will essentially improve and simplify the comparison with theoretical expectations.

The more detailed description of the structure evolution of absorbers significantly increases the number of fitting parameters for the limited available statistics of observed absorbers, and a more detailed description accompanied by a further growth in the number of fitting parameters does not seem to be justified. Hence, as a first step, we will fit the observed redshift distribution of absorbers to relations similar to the theoretically expected expressions (2.9)–(2.12), but arbitrary fitting parameters will be used instead of the functions \( b(m) \). The difference between the observed and expected redshift distributions can be attributed to the influence of omitted factors. Similar analysis can be repeated with a richer data base and/or with available numerical simulations.
2.3.1 Absorption in wall-like elements

The first term in (2.2), \( n_w \), describes the absorption associated with wall-like elements. Now these elements accumulate \( \approx 50 \) per cent of galaxies and their possible contribution cannot be rejected a priori. The observed mean separation of walls is about 40–60 \( h^{-1} \text{Mpc} \), and the comoving linear number density of such elements is \( \sigma_w(0) \approx 2.5-1.5 \times 10^{-5} \text{h Mpc}^{-3} \) (LCRS1). These elements are formed during late evolutionary stages and can be observed, primarily, at small redshifts \( z \approx 1-1.5 \).

Taking into account expressions (2.3) and (2.9), we will approximate the mean dimensionless linear number density of absorbers associated with such elements by the two-parameter function

\[
n_w(z) = \kappa_w E(c_w, z), \tag{2.13}
\]

where

\[
\kappa_w = \frac{c \sigma_w(0) \alpha_w}{H_0}, \quad E(c_w, z) = \exp \left[ - c_w [B^{-2}(z) - 1] \right]
\]

and the covering factor \( \alpha_w < 1 \) and the parameter \( c_w \) characterize the probability of the formation of an absorption line in a wall and the period of wall formation, respectively. The observed wall-like structure elements are strongly disrupted (see e.g. fig. 5 in Ramella et al. 1992) and therefore we can expect that \( \alpha_w \ll 1 \) and \( n_w(0) = \kappa_w \approx 60 \alpha_w \).

2.3.2 Absorption in filamentary elements

The second term in equation (2.2), \( n_f \), describes the absorption in filaments formed by DM, galaxies and intergalactic gas. The filamentary component of the structure accumulates \( \approx 50 \) per cent of the DM and galaxies, and forms a joint network of structure between the wall-like elements. As was noted above, the mean observed 2D surface density of galaxy filaments is estimated as \( \sigma_f(0) \approx 0.01 h^2 \text{Mpc}^{-2} \).

The mean free path between filaments depends on their surface density \( \sigma_f \) and their diameters. To find it we consider the intersection of cylindrical filaments with a typical radius of gaseous halo \( R_f \) and a random cylindrical core with radius \( r \) and length \( L \). The mean number of such intersections can be found with standard methods (Kendall & Moran 1963; Buryak, Doroshkevich & Fong 1994):

\[
\langle N_{\text{int}} \rangle = \pi \sigma_f L (r + R_f).
\]

The mean free path between such cylindrical filaments along a line of sight can be approximated by

\[
\langle l \rangle \approx L / \langle N_{\text{int}} \rangle \mid_{z=0} = (\pi \sigma_f R_f)^{-1}, \tag{2.14}
\]

while the mean length of a line of sight within a filament is \( = 2R_f \).

Taking into account expressions (2.10), we will approximate the mean dimensionless linear number density of absorbers associated with filaments by a two-parameter function

\[
n_f(z) = \kappa_f (1 + z)^2 B^{-2}(z) E(c_f, z), \tag{2.15}
\]

where

\[
\kappa_f = \frac{c}{H_0} \pi R_{\text{eff}} \sigma_f(0), \quad E(c_f, z) = \exp \left[ - c_f [B^{-2}(z) - 1] \right]
\]

and

\[
R_{\text{eff}} = \alpha_f (R_f) = \frac{\kappa_f H_0}{\pi c \sigma_f} \approx 10.6 \kappa_f \left( \frac{\sigma_f}{0.01 h^2 \text{Mpc}^{-2}} \right) h^{-1} \text{kpc}.
\]

Here, \( (R_f) \) is the mean radius of the gaseous halo of a filament, the covering factor \( \alpha_f(z) < 1 \) characterizes the probability of the formation of an absorption line within a separate filament, and the factors \( 1 + z \) and \( B^{-2}(z) \) describe the expected variation of the surface density of absorbers associated with filaments caused by the general expansion of the Universe, merging and expansion or compression of filaments. The parameter \( c_f \) characterizes the period of formation of the main fraction of observed filaments.

The mean radius of the gaseous halo of filaments, \( (R_f) \), can vary with the redshift and along the filament, because the observed galactic density varies along the filament as well. This means that our statistical estimate of averaged \( (R_f) \) is weighted by the matter distribution along the filaments at different redshifts.

More detailed models of absorbers associated with DM filaments can be developed. They depend, however, on many parameters which cannot be adequately determined from the available data base. Hence, in this paper we will restrict our consideration to the two-parameter model discussed above.

2.3.3 Absorption in low-mass structure elements

The third term in equation (2.2), \( n_{\text{pan}} \), describes absorption by low-mass structure elements. The available information about the properties of this population at small redshifts is very limited, and we can only estimate the mean linear number density of such pancakes \( n_{\text{pan}}(0) = \kappa_{\text{pan}} \). Taking into account expressions (2.12), we will approximate the mean dimensionless linear density of such absorbers as

\[
n_{\text{pan}}(z) \approx \kappa_{\text{pan}} (1 + z)^2 B^{-3}(z) E(c_{\text{pan}}, z), \tag{2.16}
\]

where

\[
E(c_{\text{pan}}, z) = \exp \left[ - c_{\text{pan}} [B^{-2}(z) - 1] \right].
\]

Here, the factors \( (1 + z)^2 \) and \( B^{-3}(z) \) describe the expected variation of the density \( n_{\text{pan}}(z) \) caused by the general expansion, merging and compression and/or expansion of pancakes in the transversal directions. The parameter \( \kappa_{\text{pan}} \) is the effective dimensionless free path between such absorbers at \( z = 0 \), and \( c_{\text{pan}} \) characterizes the period of formation of the main fraction of observed pancakes with \( N_{\text{H}_1} \gtrsim 10^{14} h^{-2} \text{cm}^{-2} \).

The expressions (2.13), (2.15) and (2.16) give probable fitting relations for the observed evolution of absorbers associated with various types of structure elements. They allow us to estimate, in principle, the effective radius of the gaseous component of filaments and the parameters of the cosmological model \( \Omega_m \) and \( \Omega_{\Lambda} \). All the fitting parameters have a clear interpretation.

Here, we do not consider the possible contribution of any high-density clouds, because they are usually embedded in DM filaments and pancakes. This contribution is small, at least at redshifts \( z \leq 3 \), and cannot be reliably singled out with the available data base, but it is probably more important at higher redshifts.

2.4 The observed linear number density of structure elements

The small-scale clustering of absorption lines has been reported in many papers (see e.g. Cristiani et al. 1995, 1996; Ulmer 1996), and it is especially important for metal systems. It implies that a complex of nearby lines can be generated in the same structure element. As we are interested in the statistics of structure...
elements, this factor must be taken into account. To do this we will use a technique developed earlier for the core-sampling method (Buryak et al. 1994; LCRS1), which allows us to select a Poisson-like subsample of points from a general sample. The redshift dependence of the mean number density of the subsample characterizes the redshift evolution of uncorrelated absorbers, which can be identified with separate structure elements.

This method uses the separation of neighbouring lines, rather than the redshift of the lines themselves, which somewhat attenuates the influence of the selection effects inherent in individual spectra. If the number of lines in a sample is \( > 30 \), we can estimate the parameters of a Poisson distribution with a reasonable precision \( \approx 10-20 \) per cent. Hence we can use the available catalogues, which is important for the metal systems as the number of such systems in individual absorption spectra is usually small.

The major points of the method can be summarized as follows.

(i) The separation between the lines is characterized by the dimensionless comoving distance

\[
\Delta l = H_0 \Delta z / H(z). 
\]  

(ii) A subsample of lines in an interval \( z - d_z < z < z + d_z \), taken from all spectra under investigation, is organized into an ‘equivalent single field’ by combining the line separations \( \Delta l \) one after the other along a line.

(iii) The distribution of absorbers obtained in that way is assumed to be Poissonian for larger separations, 1D cluster analysis is used to discriminate the Poisson-like subsample among the sample of points, and to find the number and the mean linear number density of such points. The theoretical groundwork for such an approach was developed by Buryak, Demianński & Doroshkevich (1991).

Using the standard 1D clustering analysis, the mean number of Poisson points in the sample \( N_P \) and their mean linear number density \( n_P \) are found by the maximum likelihood fitting to the relation

\[
\ln(N_l) = \ln(N_P) - n_P R_l, \tag{2.18}
\]

where \( R_l \) and \( N_l \) are the variable linking length and the related number of clusters, respectively. Note that for a truly Poissonian sample, parameters \( N_P \) and \( n_P \) are related to the length of the ‘equivalent single field’ \( D_\text{th} \) defined by the first and the farthest point by

\[
D_\text{th} / N_P = n_P. \tag{2.19}
\]

Thus, the difference between the values \( N_P \) and \( n_P \) obtained from equations (2.18) and (2.19), and variations of the actual number of clusters along a straight line (2.18) give us a measure of the error made as a result of the difference between the actual and the assumed (Poisson) distribution for absorbers along the line of sight. To decrease this error we use an automatic procedure, which finds the optimal range of \( R_i \) for the fitting to equation (2.18). Both upper and lower limits of \( R_i \) were varied to obtain the best fit for the linear number density of absorbers \( n_{\text{th}}(z) \).

As a rule, the precision of this method increases with the number of lines \( N_{\text{line}}(z) \) in the interval \( z - d_z < z < z + d_z \). For \( N_{\text{line}}(z) > 50 \), any random variation does not exceed 10 per cent, and the real error is defined by the systematic variations of the sample under investigation. For smaller \( N_{\text{line}}(z) \), random variations become essential. This condition restricts the choice of the optimal interval to \( d_z = 0.2-0.25 \).

### 3 THE DATA BASE

The present analysis is based on spectra available in the literature. The list of such objects is given in Table 1.

The distribution of lines over redshift is nonhomogeneous and the majority of lines are concentrated at \( z \approx 0.3 \). Using the technique described above, we can obtain the linear density of a Poissonian subsample of absorbers, at \( z \approx 0.3 \), with a reasonable precision of about 10–20 per cent. The distribution of absorbers at \( z \approx 0.3 \) is based primarily on the 430 lines of QSO 0000–260 (Luh et al. 1996), and here the statistics of the lines are rather poor. Inclusion of the spectrum of QSO 1033–033 extends the redshift interval up to \( z \approx 4.4 \), but it cannot improve inadequate representativeness of the sample at \( z \approx 3.2 \). Samples of poorer lines, with \( \log N_{\text{HI}} \approx 13 \), are incomplete at all redshifts.

A few samples of observed metal systems were analysed. Here we present results obtained for the richest recent sample (Vanden Berk et al. 1999). This catalogue contains 901 separations between lines of neighbouring metal systems from 237 spectra of quasars at redshifts \( 0 \leq z \leq 3.5 \).

The published Ly\( \alpha \) lines with different \( N_{\text{HI}} \) were organized into six samples listed in Table 2. All samples were supplemented by the Hubble Space Telescope (HST) data (Bahcall et al. 1993, 1996; Jannuzi et al. 1998). The samples with \( N_{\text{HI}} \approx 13.8 \) are associated mainly with the filamentary component of the structure, whereas samples with \( N_{\text{HI}} \approx 13 \) and \( N_{\text{HI}} \approx 12 \) are associated predominantly with the poor pancakes.

### Table 1. QSO spectra from the literature.

| Name       | \( z_{\text{em}} \) | \( z_{\text{min}} \) | \( z_{\text{max}} \) | FWHM | No of lines |
|------------|----------------------|-----------------------|-----------------------|------|-------------|
| 1331+170\(^1\) | 2.10 | 1.7 | 2.1 | 18 | 69          |
| 1101–264\(^2\) | 2.15 | 1.8 | 2.1 | 9  | 84          |
| 1225+317\(^3\) | 2.20 | 1.7 | 2.2 | 18 | 159         |
| 1946+766\(^4\) | 3.02 | 2.4 | 3.0 | 8  | 461         |
| 0636+680\(^5\) | 3.17 | 2.5 | 3.0 | 8  | 313         |
| 0302–003\(^6\) | 3.29 | 2.6 | 3.1 | 8  | 266         |
| 0956+122\(^7\) | 3.30 | 2.6 | 3.1 | 8  | 256         |
| 0014+813\(^8\) | 3.41 | 2.7 | 3.2 | 8  | 262         |
| 0000–260\(^9\) | 4.11 | 3.4 | 4.1 | 7  | 431         |
| 2126–158\(^10\) | 3.26 | 2.9 | 3.2 | 11 | 130         |
| 0055–259\(^11\) | 3.66 | 2.9 | 3.1 | 14 | 313         |
| 1700+642\(^12\) | 2.72 | 2.1 | 2.7 | 15 | 85          |
| 2206–199\(^13\) | 2.56 | 2.1 | 2.6 | 11 | 101         |
| 1033–033\(^14\) | 4.50 | 3.7 | 4.4 | 18 | 299         |

\(^1\)Kulkarni et al. (1996); \(^2\)Carswell et al. (1991); \(^3\)Khare et al. (1997); \(^4\)Kirkman & Tytler (1997); \(^5\)Hu et al. (1995); \(^6\)Lu et al. (1996); \(^7\)Giallongo et al. (1993); \(^8\)Cristiani et al. (1995); \(^9\)Rodríguez et al. (1995); \(^10\)Rauch et al. (1993); \(^11\)Williger et al. (1994). 

### Table 2. Samples of absorbers.

| Sample | \( N_{\text{QSO}} \) | \( \log N_{\text{HI}} \) | \( N_{\text{lines}} \) | \( N_{\text{HST lines}} \) | \( W_{\text{HST}} \) |
|--------|---------------------|------------------------|-----------------------|-----------------------|------------------|
| \( Q_{14} \) | 14 | 14 | 686 | 590 | 0.5 |
| \( Q_{13} \) | 14 | 13.8 | 971 | 590 | 0.5 |
| \( Q_{14} \) | 14 | 13.0 | 2351 | 933 | 0.25 |
| \( Q_{12} \) | 12 | 13.0 | 1986 | 933 | 0.25 |
| \( Q_{14} \) | 14 | 12.0 | 3177 | 1000 | 0.0 |
| \( Q_{12} \) | 12 | 12.0 | 2780 | 1000 | 0.0 |

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4 STATISTICAL ANALYSIS OF STRUCTURE EVOLUTION

In this section the main results are presented for the redshift distribution of both Lyα lines and metal systems. They confirm that the redshift distribution of Lyα lines is a superposition of several populations with different evolutionary histories (Bahcall et al. 1996). Using the method and the fitting relations discussed in Section 2 for the analysis of samples with different N_H, we can roughly discriminate two populations of absorbers and describe their evolution. Our estimates use essentially the HST data for z ≲ 1.5.

For three cosmological models, the distribution of absorbers was fitted to the expression

\[ n_{\text{abs}} = \frac{\kappa_1 (1 + z)}{B_0(z)} E(c_{f}, z) + \frac{\kappa_{\text{pan}} (1 + z)^2}{B_1(z)} E(c_{\text{pan}}, z) \]  

(4.1)

where

\[ E(c, z) = \exp[-c(B^{-2}(z) - 1)]. \]

The function B(z) was introduced in equation (2.3). The main results are plotted in Figs 1–5, and the best-fitting parameters \( \kappa_{f} \), \( c_{f} \), \( \kappa_{\text{pan}} \) and

\[ R_{\text{eff}} = \frac{\kappa_1 H_0}{\pi c \sigma_f} = 10.6 \kappa_1 \left( \frac{\sigma_f}{0.01 h^2 \text{Mpc}^{-2}} \right) h^{-1} \text{kpc}, \]

(4.2)

are listed in Tables 3–5. For samples of richer absorbers \( c_{\text{pan}} = 0 \), whereas for samples of poorer absorbers \( c_{\text{pan}} = 0.05 \pm 0.05 \) was found with large errors, and so it is omitted in Table 4.

4.1 The redshift distribution of metal systems and stronger H I lines

It can be expected that the redshift distribution of metal systems and stronger Lyα lines is connected with the evolution of richer structure elements, which are seen in galaxy surveys as filaments and walls. To examine this hypothesis the function \( n_{\text{abs}}(z) \) was found for the sample of metal systems and the samples of strongest Lyα lines, \( Q_{138}^4 \) and \( Q_{138}^{14} \). The analysis shows that in all cases no more than 10–15 per cent of all lines can be attributed to the massive wall-like elements, consistent with the large separation of walls (\( \gtrsim 50 h^{-1} \text{Mpc} \)) and their strong disruption into a system of high-density clouds, which decreases their covering factor.

For all the cosmological models considered, the redshift distributions of Lyα absorbers for samples \( Q_{138}^4 \) and \( Q_{138}^{14} \) are well fitted, for \( z \leq 3 \), by the one-parameter function (4.1) with \( c_{f} = 0 \) and \( \kappa_{\text{pan}} = 0 \). The redshift distribution of metal systems is well fitted by the two-parameter function (4.1) with \( \kappa_{\text{pan}} = 0 \). The best parameters of these fittings are listed in Table 3. They show that metal systems are predominantly formed within inner regions of the gaseous haloes of filaments, the sizes of which \( R_{\text{eff}}^{\text{met}} \) are about half the size of the hydrogen haloes \( R_{\text{eff}}^{\text{H}} \). Both sizes are

**Figure 1.** \( n_{\text{abs}} \) versus \( z \) for metal systems in cosmological models with (a) \( \Omega_m = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \), (b) \( \Omega_m = 0.5 \) and \( \Omega_{\Lambda} = 0 \) and (c) \( \Omega_m = 1 \).

**Figure 2.** The redshift distribution of absorbers for samples \( Q_{138}^4 \) (points and solid lines) and \( Q_{138}^{14} \) (triangles and long-dashed lines), for cosmological models with (a) \( \Omega_m = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \), (b) \( \Omega_m = 0.5 \) and (c) \( \Omega_m = 0 \) and \( \Omega_{\Lambda} = 1 \). The dotted lines show the best two-parameters fitting for the filamentary component only at \( z < 3 \).
consistent with the sizes observed directly at small $z$: $R_{HI} \sim 100-150$ $h^{-1}$ kpc (Lanzetta et al. 1995) and $R_{\text{met}} \sim 40-50$ $h^{-1}$ kpc (see e.g. Le Brune et al. 1996), and with the expected size of the DM halo (Bahcall et al. 1996). The precision of the estimates for $R_{\text{eff}}$ depends on the representativeness of the sample used.

These results suggest that the redshift distribution and the column density of absorbers are strongly correlated, and that they corroborate the identification of strong H I absorbers and metal systems, with the filamentary component of the structure of the Universe. They show that such filaments were probably formed at redshifts $z \geq 2$, but their enrichment by metals could occur later at redshifts $z \approx 2$ and smaller.

At redshifts $z \geq 3$ the situation becomes more complicated, and the observed absorber distribution is no longer described by the one-parameter fit plotted in Fig. 2 by dotted lines. To obtain a reasonable description, even for the redshift distribution of stronger absorbers at $z \geq 3$, the three-parameter fitting of equation (4.1) with $c_{\text{pan}} = 0$ must be used. This indicates that at $z \geq 3$ a progressively increasing part of stronger absorbers must be assigned to pancakes.

The best parameters of these fittings are listed in Table 4, and fitting functions $n_{\text{abs}}(z)$ are plotted in Fig. 2 by solid and long-dashed lines. These estimates of $c_{\text{f}}$ and $R_{\text{eff}}$ crucially depend on the region of redshifts $2.5 \leq z \leq 3.3$, and could be sensitive to the possible evolution of filaments. They show that the formation of such filaments described by the exponential term in (4.1) could occur at redshifts $z \geq 1$, while later the surface density of filaments progressively decreases. The effective radii listed in Table 4 exceed by about 2–3 times the values listed in Table 3 for smaller redshifts. This fact can be attributed to the progressive compression, small-scale disruption, and relaxation of DM within and around the filaments, which is accompanied by the progressive dissipation of the gaseous haloes of the filaments. The observed evolution can also be partly assigned to the variations of background ultraviolet radiation with redshift.

At redshifts $z \geq 2.5$, a more and more essential fraction of strong absorbers is associated with rich pancakes and, at $z \geq 3.5$, the pancakes become dominant, even for this population. This fact probably indicates a period of more rapid transformation of rich pancakes into filaments.

This conclusion is based on poor statistics of absorbers, at $z \geq 3$, and should be tested with a more representative sample of absorbers and with simulations.

For our samples, the parameters of a standard fitting with $\frac{dN}{dz} = N_0(1 + z)^\gamma$ are

$$N_0^{\text{met}} = 6.8 \pm 0.5, \quad \gamma^{\text{met}} = 0.35 \pm 0.25,$$
$$N_0^{HI} = 12.7 \pm 2, \quad \gamma^{HI} = 1.5 \pm 0.3$$

(4.4)

with a weak dependence on the cosmological models considered considered.
4.2 The redshift distribution of weaker Lyα lines

The samples of weaker absorbers are rich enough, but even so the main fraction of the absorbers observed is concentrated near \( z \approx 2.5 - 3.3 \). In Figs 3 and 4 the functions \( n_{\text{abs}}(z) \) are plotted for the samples \( Q_{13}^{14} \) and \( Q_{13}^{13} \), and \( Q_{13}^{12} \), together with the four-parameter fittings of equation (4.1). Both samples of poor absorbers with \( \log N_{\text{HI}} \leq 13 \) are incomplete. The best-fitting parameters \( \kappa_f, \kappa_m, \kappa_{\text{pan}} \) and \( \sigma_{\text{pan}} \) listed in Table 4 are weakly sensitive to the cosmological models used.

These results show that, at redshifts \( z \approx 1.5 - 2 \), an essential fraction of weaker absorbers can be associated with the periphery of filaments and/or with possible membranes and bridges between branches of filaments, which is consistent with the expectations of Fernandes-Soto et al. (1996). But at high redshifts, the main fraction of poorer absorbers is certainly identified with the population of low-mass pancakes and, for \( N_{\text{HI}} \leq 10^{13} \text{ cm}^{-2} \), with absorbers formed within expanded regions. The small value of \( \kappa_{\text{pan}} \) suggests that these absorbers were formed at \( z \approx 4 - 5 \). These estimates are sensitive to the distribution of absorbers at \( z \approx 3 \), where the observed samples are not sufficiently representative. For these populations the random overlapping of poor absorbers in the redshift space, discussed by McGill (1990) and Levshakov & Kegel (1998), formation of absorbers within ‘minivoids’ (Zhang et al. 1998; Dave et al. 1999) as well as the variations of ultraviolet background, can distort the observed mass and temperature distribution of absorbers. As was noted in Section 2.1.2 at these redshifts, the more complicated three-parameter function (2.11) provides a better fitting of the observed distribution of absorbers.

The essential variations of the measured linear density \( n_{\text{abs}} \) with respect to the smooth fitting functions are seen in Figs 3 and 4 at \( z \approx 2.5 - 3 \). They can be caused, in part, by the poor statistics of absorbers at \( z \approx 2.5 \) and \( z \approx 3 \). If the variations seen at \( z \approx 3 \) are real they can be connected with similar results obtained for the population of stronger absorbers and, thus, can indicate the period of fast transformation of pancakes into filaments. They can also be

### Table 3. Fitting parameters for the filamentary component at \( z \approx 3 \).

| \( \Omega_m \) | \( \Omega_{\Lambda} \) | \( R_{\text{eff}}^{\text{fil}} \) | \( c_f^{\text{fil}} \) | \( \kappa_{\text{pan}}^{\text{fil}} \) |
|-------------|----------------|----------------|----------------|---------------|
| 1.0         | 0.0            | 40 ± 1.5       | 0.07 ± 0.03    | 98 ± 2.4      |
| 0.5         | 0.0            | 52 ± 1.6       | 0.15 ± 0.04    | 118 ± 3.3     |
| 0.3         | 0.7            | 38 ± 1.7       | 0.13 ± 0.04    | 69 ± 3.5      |

### Table 4. Fitting parameters of distribution of absorbers redshifts for three cosmological models.

| Sample | \( \kappa_f \) | \( R_{\text{eff}}^{\text{fil}} \) | \( c_f^{\text{fil}} \) | \( \kappa_{\text{pan}}^{\text{fil}} \) |
|--------|----------------|----------------|----------------|----------------|
| \( Q_{14}^{14} \) | 22 ± 1.3       | 2.2 ± 0.1      | 0.34 ± 0.14    | 0.75 ± 0.12    |
| \( Q_{13}^{18} \) | 21 ± 1.2       | 2.1 ± 0.1      | 0.33 ± 0.15    | 0.91 ± 0.11    |
| \( Q_{13}^{13} \) | 43 ± 1.5       | 4.3 ± 0.1      | 1.0 ± 0.20     | 4.2 ± 0.11     |
| \( Q_{13}^{12} \) | 43 ± 1.3       | 4.3 ± 0.1      | 1.0 ± 0.20     | 3.7 ± 0.11     |
| \( Q_{14}^{12} \) | 45 ± 1.6       | 4.4 ± 0.1      | 1.1 ± 0.22     | 4.8 ± 0.11     |
| \( Q_{12}^{12} \) | 49 ± 2.1       | 4.8 ± 0.2      | 1.1 ± 0.21     | 4.0 ± 0.09     |

### Table 5. Fitting parameters for the subsamples of absorbers \( Q_{13}^{12} \) with \( b > 40 \text{ km s}^{-1} \) and \( b < 20 \text{ km s}^{-1} \)

| Sample | \( \kappa_f^{\text{fil}} \) | \( \kappa_{\text{pan}}^{\text{fil}} \) | \( 10^3 \) |
|--------|----------------|----------------|-----------|
| \( \Omega_m = 0.3 \), \( \Omega_{\Lambda} = 0.7 \) | 23 ± 1.2 | 2.2 ± 0.1 | 0.6 ± 0.16 |
| \( \Omega_m = 0.5 \), \( \Omega_{\Lambda} = 0.3 \) | 18 ± 1.0 | 1.7 ± 0.1 | 0.6 ± 0.18 |

c_{\text{pan}} \approx 0.03 - 0.05 suggests that these absorbers were formed at \( z \approx 4 - 5 \). These estimates are sensitive to the distribution of absorbers at \( z \approx 3 \), where the observed samples are not sufficiently representative. For these populations the random overlapping of poor absorbers in the redshift space, discussed by McGill (1990) and Levshakov & Kegel (1998), formation of absorbers within ‘minivoids’ (Zhang et al. 1998; Dave et al. 1999) as well as the variations of ultraviolet background, can distort the observed mass and temperature distribution of absorbers. As was noted in Section 2.1.2 at these redshifts, the more complicated three-parameter function (2.11) provides a better fitting of the observed distribution of absorbers.

The essential variations of the measured linear density \( n_{\text{abs}} \) with respect to the smooth fitting functions are seen in Figs 3 and 4 at \( z \approx 2.5 - 3 \). They can be caused, in part, by the poor statistics of absorbers at \( z \approx 2.5 \) and \( z \approx 3.5 \). If the variations seen at \( z \approx 3 \) are real they can be connected with similar results obtained for the population of stronger absorbers and, thus, can indicate the period of fast transformation of pancakes into filaments. They can also be
The parameters of the standard fitting of equation (4.3) are

\[ N_0^{\text{pan}} = 13.8 \pm 0.6 \quad \text{and} \quad \gamma_c^{\text{pan}} = 2.4 \pm 0.2, \quad \text{for} \quad Q_{12}^3 \]

and

\[ N_0^{\text{pan}} = 11.8 \pm 0.6 \quad \text{and} \quad \gamma_c^{\text{pan}} = 2.75 \pm 0.2, \quad \text{for} \quad Q_{12}^5, \quad (4.5) \]

with a weak dependence on the parameters of the cosmological models considered. The power index \( \hat{s}^{\text{pan}} \) is close to the value found previously (see e.g. Carswell 1995; Cristiani et al. 1996).

### 4.3 The redshift distribution of Ly\( \alpha \) lines with \( b \approx 40 \text{ km s}^{-1} \) and \( b \approx 20 \text{ km s}^{-1} \)

The same technique can be applied to single out other subpopulations of absorbers such as subpopulations with a lower Doppler parameter \( b \approx 20 \text{ km s}^{-1} \), and larger \( b \approx 40 \text{ km s}^{-1} \). The main results of this analysis are plotted in Fig. 5 and the best fitting parameters are listed in Table 5. Unfortunately, they cannot be complemented by HST data at smaller redshifts.

These subpopulations are not so representative and at \( z \leq 4 \), they contain only 640 lines with \( b \approx 20 \text{ km s}^{-1} \) and 727 lines with \( b \approx 40 \text{ km s}^{-1} \). This is the main source of the large errors on the fitting parameters listed in Table 5. None the less, these results demonstrate that if the subpopulation of hot absorbers with \( b \approx 40 \text{ km s}^{-1} \) can be associated with pancakes, then the redshift distribution of cold absorbers with \( b \approx 20 \text{ km s}^{-1} \) is similar to that found for the filamentary component of the structure.

### 5 SUMMARY AND DISCUSSION

In this paper the observed redshift distributions of Ly\( \alpha \) lines and metal systems are analysed and interpreted in the framework of the theoretical model of DM structure evolution (DD99). The observed evolution of absorbers depends on several random factors and does not trace directly the evolution of the DM component. Our results show, however, that the observed redshift distributions of absorbers can be reasonably described even by the discussed model.

The main results of our analysis can be summarized as follows.

(i) The different redshift distributions of stronger and weaker absorbers favour the existence of two distinct subpopulations of Ly\( \alpha \) absorbers: a rapidly evolving subpopulation of weaker absorbers that dominates at high redshifts, and a more slowly evolving subpopulation of stronger absorbers that dominates at low redshifts (Bahcall et al. 1996). This result coincides with theoretical expectations.

(ii) The expected evolution of the filamentary component of structure adequately describes the redshift distribution of metal systems, and stronger Ly\( \alpha \) lines, at \( z \leq 3 \). This strong correlation of evolutionary rate and the column density of absorbers suggests a possible identification of stronger absorbers with the filamentary component of observed galaxy distribution.

(iii) The subpopulation of colder absorbers, with \( b \approx 20 \text{ km s}^{-1} \), can probably be related with the filamentary component of the structure.

(iv) The rapid evolution of the linear number density of weaker absorbers \( n_{\text{abs}} \) can be naturally explained by the model of separate DM-confined pancakes that are merging, and expand or contract in the transversal direction, as described by the theoretical model discussed above. At \( z \approx 2 \), disruption of the compressed matter can essentially accelerate the evolution of this subpopulation.

(v) The observed redshift distribution of absorbers depends on the influence of irregular local factors, such as the variations of background ultraviolet radiation, and shock heating of gas produced by the activity of galaxies. This impact is seen as irregular variations of the observed linear number density of absorbers around the smooth fitting curves.

(vi) The obtained estimates of \( c_1 \) can be interpreted as a possible pick of the rate of formation of filaments at \( z \approx 2 \), whereas their enrichment by the metals can occur at \( z \approx 2 \) and smaller. The small values of \( c_{\text{pan}} \), found for all subpopulations under investigation, show that the main fraction of the poor absorbers observed can be associated with DM structure elements formed at redshifts \( z \approx 5 \).

The main quantitative characteristics of the redshift distribution of absorbers, discussed above, enable a natural interpretation and coincide with published estimates (see e.g. Cristiani 1995, 1996; Hu et al. 1995; Lanzetta et al. 1995; Bahcall 1996; Le Brune 1996). They are roughly consistent with the expected evolution of DM structure and can be, in principle, used to test and to discriminate between different cosmological models. Now the best fit is obtained for the model with \( \Omega_m = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \), but a more representative data base at redshifts \( z \sim 2-2.5 \) and \( z \gtrsim 3 \) is required for more reliable discrimination between cosmological models.

On the other hand, the rough model of structure evolution discussed ignores many details, such as, for example, the continual variation of morphological characteristics of structure elements, and does not describe the disruption of structure. This model could be improved, but this will inevitably increase the number of fitting parameters, and so it will only be justified when richer sets of observed absorbers, especially at smaller and higher redshifts, become available. This comment also applies to the more detailed description of expected variations of ultraviolet radiation, and the possible contribution of artificial caustics. Application of this approach to available simulations could also test and improve it.

The wall-like structure elements and large underdense regions found in the distribution of galaxies at small redshifts cannot yet be reliably identified with the available data base. The large-scale modulation of redshift distribution of Ly\( \alpha \) lines found by Cristiani et al. (1997), and the strong nonhomogeneities, found recently at \( z \lesssim 2 \) by Williger et al. (1996), Quashnock, Vanden Berk & York (1996, 1998) and Connolly et al. (1996), probably could be attributed to such rare extremely rich structure elements. Appearance of such elements is not forbidden for any redshifts, but it can be expected that their number will rapidly decrease for larger redshifts.

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