On the Small-Scale Clustering of the Lyα Forest Clouds

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ABSTRACT

Recent measurements of the autocorrelation function of the Lyα clouds are analyzed from the point of view of a simple model with strong clustering on the small scales. It is shown that this toy model reproduces fairly well the important linear relation between amplitude of the absorber autocorrelation function and neutral hydrogen column density. In addition, it predicts a correct evolutionary trend of correlation amplitudes. Some possible ramifications of these results are discussed.

Key words: quasars: absorption lines—intergalactic medium—galaxies: haloes—galaxies: evolution

1 INTRODUCTION

The problem of clustering of the Lyα forest absorbers has been discussed in the course of the last two decades by many authors (Sargent et al. 1980; Dekel 1982; Salmon & Hogan 1986; Webb 1987; Ostriker, Bajtlik & Duncan 1988; Crotts 1989; Heisler, Hogan & White 1989; Liu & Jones 1990; Webb & Barcons 1991; Barcons & Webb 1990; 1991; Fang 1991; Mo et al. 1992; Fardal & Shull 1993; Srianand & Khare 1994; Chernomordik 1995; Elowitz, Green & Impey 1995; Meiksin & Bouchet 1995; Carbone & Savaqlio 1996; Srianand 1996; Ulmer 1996; Fernández-Soto et al. et al. 1996; Lanzetta, Webb & Barcons 1996; Pando & Fang 1996; Cen & Simcoe 1997; Rauch 1998). The conclusions of the entire effort are still controversial, since the original paradigm that Lyα clouds do not show no clustering at all (Sargent et al. 1980; Barcons & Webb 1990), was somewhat undermined by findings of weak clustering of intermediate-redshift Lyα clouds (Webb 1987; Barcons & Webb 1991; Webb & Barcons 1991; Chernomordik 1995), and seriously questioned by the work on associated C IV absorption (Cowie et al. 1995; Fernández-Soto et al. 1996; see also Songaila & Cowie 1996). As Dekel writes: "My aim is to point out a cosmological scenario in which galaxies are clustered only weakly at z > 1.7, so that the LACs [Lyα clouds] may cluster just like galaxies. Here both the isothermal and the truncated adiabatic components of the density perturbations play a role in the formation of structure in the universe." It is also quite interesting to note that Dekel (1982) was the first to suggest usage of C IV lines to measure the degree of clustering of absorption systems, idea which was fully realized only 14 years later by Fernández-Soto et al. (1996). It should certainly be mentioned that low spectral resolution of most of existing measurements (e.g. 250 – 300 km s$^{-1}$ for the HST Key Project; see Jannuzi 1997; Jannuzi et al. 1998) makes investigations on small scales exceedingly difficult. And it is exactly these scales which are, because of their discrimination power, the most interesting from our point of view.

Webb (1987) was the first to point out the presence of weak clustering at small velocity scales, based on the Voigt profile fitting in the high-redshift data, which was confirmed by other investigations (e.g. Muecket & Mueller 1987). As emphasized by Fernández-Soto et al. (1996), it is very difficult to directly detect clustering of the Lyα lines because of the short redshift path length in any individual QSO spectrum, and line blending. If a significant fraction, or most of the observed Lyα absorption lines are in fact blends of very narrow components, detected amplitudes of the autocorrelation function would be significantly underestimated (see also a discussion in Rauch et al. 1992).

On the basis of these early findings, Ostriker et al. (1988) first proposed gravitationally induced clustering...
as one of the possible explanations for excess of pairs of absorbers at small (and in their sample, intermediate) velocity splittings. However, in a recent important study, Cristiani et al. (1997), performed the most comprehensive analysis of the clustering of Lyα clouds in a sample of about 1600 absorbers along 15 lines of sight, and concluded that the small-scale clustering of Lyα absorbers (a) is real, and (b) can be understood in terms of gravitationally-induced clustering, in the manner of Ostriker et al. (1988). Parenthetically, the existence of structure in the Lyα forest was confirmed by independent methods aimed at detection of the deviation of spatial distribution of absorbers from a uniform random one; thus Fang (1991) showed that Lyα forest deviate from a uniform distribution at 3σ significant level. This is, of course, still weaker from the non-uniformity seen among the known galactic population, but very different from the picture of uniform, diffuse intergalactic population envisaged by Sargent et al. (1980).

Another recent work of great importance for the development of our ideas on the spatial distribution of Lyα clouds is that of Ulmer (1996), who investigated a sample of low-z Lyα lines recently obtained with the HST Key Project (Bahcall et al. 1996). Results of that work are particularly significant, since they demonstrate the existence of strong clustering of Lyα lines at velocity separations at which high-z lines seem completely unclustered, and which represent an intermediate regime between the small-scale (Δv < 200 km s\(^{-1}\)) and large scale clustering. In physical terms, we can hypothesize that the small-scale regime can be plausibly explained as characteristic of the intragalactic motions in typical L ∼ L∗ galaxies, being on the same order as velocity dispersion in the known galactic subsystems (Binney & Tremaine 1987). On the other hand, large-scale clustering is generally believed to trace large-scale structure (i.e. structures with velocity dispersions similar to that in rich galaxy clusters and higher). Ulmer (1996) has not obtained any information on the small velocity splittings, since his method explicitly rejects velocity splittings with Δv < 250 km s\(^{-1}\). Still, its implications are important because of the very strong signal found for 250 ≤ Δv ≤ 500 km s\(^{-1}\), which, if extrapolated into Δv < 250 km s\(^{-1}\) agrees well with results of Cristiani et al. (1997) and those discussed in further text. Similar excess of absorber pairs for Δv ∼ 200 km s\(^{-1}\) was found by Srianand & Khare (1994) at the ∼ 4σ level. The redshift evolution of clustering is also correctly emphasized in Ulmer (1996), who inferred a substantial increase in the degree of clustering of the Lyα forest. As we shall see, there is evidence that the same trend is real over most of the history of the universe.

In the rest of this paper, we shall attempt to show that the results of Ulmer (1996) and Cristiani et al. (1997) for the amplitude of TPCF are consistent with simple model characterized by constant small-scale clustering. Specifically, we shall show that (i) the linear relation between column density of clouds and their autocorrelation amplitude, and (ii) the general evolutionary trend of decrease in clustering with increasing redshift, are successfully explained in such a toy model. Following two sections are, therefore, devoted to these two important issues. Although not specifically endorsing such a simplistic approach, it does make the complex explanations for the observed TPCF properties, involving biasing for the structure formation and gravitationally induced correlations, unnecessary. In contradistinction, models in which the Lyα forest is locally decoupled from the Hubble flow and physically associated with collapsed structures (e.g. galaxies) predict, in general, exactly such a behavior.

2 A SIMPLE MODEL

Let the Lyα cloud distribution function (neglecting the Doppler parameter dependence) be written in the standard form as (e.g. Lu et al. 1996):

\[ F(N, z) = \frac{\partial n}{\partial z} \partial N_{H1} = A_0 (1 + z)^\gamma N_{H1}^{-\beta}. \]  

(1)

Constants in equation (1) were measured by various authors (Hu et al. 1995; Lu et al. 1996; Kim et al. 1997). For our purpose, it is enough to take approximate values \( \gamma = 2.75 \), and \( \beta = 1.55 \) for the indices of redshift and column density distribution respectively. One of the ways to simplify relation (1) is to consider only column density dependence in a sufficiently large sample of absorbing lines. This column density distribution function we shall denote by \( f(N) \), and its standard functional form as

\[ f(N) = BN^{-\beta}. \]  

(2)

Normalization for \( f(N) \) is given as \( B = 9.2 \times 10^8 \) (Lu et al. 1996).

Let us consider a simple model in which absorbers along the line of sight are clustered around given points along the line of sight with small-scale clustering described by \( \phi(v) \) in the form of the step function, such that

\[ \phi(v) = \begin{cases} \phi(v) = \text{const.} & v \leq \sigma_{\text{max}} \\ 0 & v > \sigma_{\text{max}} \end{cases} \]  

(3)

Here, \( \sigma_{\text{max}} \) is the maximum total velocity dispersion characteristic for Lyα absorption systems, i.e. both intragalactic and intergalactic, although at this stage its physical origin is not crucial. Following Fernández-Soto et al. (1996), we shall take a fiducial value \( \sigma_{\text{max}} = 150 \) km s\(^{-1}\) (see also Crotts 1989; Mo et al. 1992).

The TPCF is, in general, defined by the probability

\[ dP = (1 + \xi)n_a dv. \]  

(4)

For our simple model of clouds concentrated around given points along the line of sight the differential probability of finding another cloud at velocity separation \( dv \) is simply

\[ dP = \phi(v) dv + n_a dv. \]  

(5)

In these relations, \( n_a \) is the average absorber density along the entire line of sight given as

\[ n_a(N_{\text{min}}, z) = \int_{N_{\text{min}}}^{\infty} F(N, z) dN \, dz. \]  

(6)

Consistency requires that probabilities in eqs. (4) and (5) are equal. It immediately follows that

* which has not been confirmed afterwards; see the discussion in Chernomordik (1995).
\[ \xi = \frac{\phi(v)}{n_a} = \int_{N_{\text{min}}}^{N} f(N)f(N)dN = \frac{\beta - 1}{B} \phi(v)N_{\text{min}}^{\beta - 1}, \]  

(7)

which gives the amplitude of TPCF as a function of threshold column density \( N_{\text{min}} \). Assumption here is that the column density distribution function stays the same at all redshifts (i.e. along the entire line of sight), enabling us to suppress the epoch dependence in \( \phi \). Notice that in this model the quantity \( \phi(v) \) is determined by the extrapolated unity column density correlation through relation

\[ \log \xi(N = 0) = \log \phi(v) + \log \frac{\beta - 1}{B}. \]  

(8)

Note that up to this point it does not matter whether \( \phi(v) \) is constant within some velocity range, as we supposed in eq. (1). From the mathematical point of view, this hypothesis remains unnecessary; however, in order to establish firm contact with correlation observations of necessarily very limited velocity resolution, we shall henceforth explicitly assume \( \phi(v) = \phi \) for small velocity splittings. (Another reason, as we shall see, becomes manifest when the redshift evolution of clustering is investigated.)

This is certainly the simplest conceivable model of the small-scale clustering: we have taken everything constant, except for the absorber number density. Calculation performed using above listed numerical values of various parameters of the distribution function and the data set of Cristiani et al. (1997) shows that (\( \log \xi, \log N_{\text{min}} \)) curve is very well approximated by a linear dependence giving a value of

\[ \log \phi = 0.16. \]  

(9)

This result is shown in Figure 1. Obvious correlation is accounted for by our toy model under the assumptions discussed above. The theoretical slope \( a_{\text{th}} \) of the linear fit \( y = ax + b \) is determined just by the index of the column density distribution

\[ a_{\text{th}} \equiv \beta - 1 = 0.55 \pm 0.05, \]  

(10)

(if we consider the best fit of Lu et al. [1996] as reliable), independent of \( \phi \). We see that the empirical slope

\[ a_{\text{emp}} = 0.64 \pm 0.06, \]  

(11)

is equal to the prediction \( \phi \) within uncertainties. This fact lends a strong support to our hypothesis.

The value of \( \phi \) in eq. (3) should be regarded as the lower limit for small-scale clustering, since it includes the lowest column density point in Cristiani et al. (1996) data, corresponding to the column density below the break in the distribution (Hu et al. 1995), for which not only should the different value of the exponent in the distribution function used in evaluating \( \phi \), but the very question of the possibility of the interpretation of these, lowest column density systems in the framework of our model is doubtful. In Figure 1 we see that a linear fit corresponding to constant clustering on the small scales is quite satisfactory with the significance of \( \sim 84 \% \). It may be noticed that the only significant non-linearity appears at the smallest column densities, where a diffuse, truly intergalactic population is expected; the toy model is inapplicable to these clouds.

with findings of Chen et al. (1998) that column density of halo clouds sharply declines with galactocentric distance; since that study also establishes a well-defined maximal radius for absorption (\( R_{\text{max}} \sim 174 h^{-1} \) kpc for \( L^+ \) galaxies), it is clear that there is a threshold column density, below which clouds can not be associated with galaxies. It is obvious that the log \( N_{\text{HI}} = 13.30 \) cm\(^{-2} \) point shows the poorest agreement with the linear fit, and excluding it from the fit gives unchanged slope \( a_{\text{emp}} = 0.59 \pm 0.06 \) (showing a satisfactory stability of our model). Although the value of \( \log \xi(N = 0) \) is still within uncertainties equal to the previous value, the central value of \( \phi \) is, however, different by the factor of about 4, since we are dealing with the unfortunate near-cancellation of two large factors. If this lowest column density point is discarded, the resulting linear fit is significant on the \( \approx 96 \% \) level. Although the number of data points is small, the general conclusion is that the more realistic fit will tend to give larger values of \( \phi \) and hence the stronger clustering than that given by eq. (1).

3 REDSHIFT EVOLUTION

A trend of decreasing clustering with increasing redshift may also be explained by small-scale constant clustering model. Since the number density of the absorbers counted from any fiducial column density \( N_{\text{min}} \) upward increase as

\[ \frac{dN}{dz} \propto (1 + z)^{\xi}, \]  

(12)

we could expect from the Equation (10) that in a fixed velocity bin, the TPCF amplitude will behave as inverse number density of absorbing clouds, i.e.

\[ \xi \propto (1 + z)^{\xi - 1}, \]  

(13)
Figure 2. The redshift dependence of the TPCF amplitude in the first (100 km s$^{-1}$). With $z_{\text{med}}$ we denote the median redshift in each of the three redshift bins of Cristiani et al. (1997). This trend is not noticed at $v > 200$ km s$^{-1}$, which can be accounted for, since only very weak clustering is expected above some maximum velocity dispersion $\sigma_{\text{max}}$, which value is set by the physics of extended gaseous haloes.

i.e. decrease with increasing redshift. Again, this is valid for fixed $v \leq \sigma_{\text{max}}$. Although the data presented in Figure 2 are certainly insufficient to achieve firm conclusions in this regard, they are nevertheless suggestive. We notice the decrease in the TPCF amplitude quite clearly in the first ($v = 100$ km s$^{-1}$) bin, much less pronounced in the second (keep in mind that we set $\sigma_{\text{max}} = 150$ km s$^{-1}$), and completely nonexistent for larger velocity separations. It is very difficult to infer any quantitative relation from data as such, but we note that the observed decrease between the first and the third redshift bin at 100 km s$^{-1}$ separation is within a 20% from the theoretical value produced by the simple model, using Kim et al. (1997) value for the high-$z$ Lyo clouds $\zeta = 2.78 \pm 0.71$ (but uncertainties are quite large). The main conclusion that clustering decreases with increasing redshift is incompatible with those classical intergalactic models of Lyo clouds in which the Hubble expansion and evolution of metagalactic background are only forces driving evolution of absorbing material, such as pressure-confined models of Sargent et al. (1980) or Ostriker & Ikeuchi (1983). The data point with $1 + z_{\text{med}} = 1.7$ from Ulmer (1996) is included in Fig. 2, although it corresponds to larger velocity scales and is not directly comparable to the other data points. Our motivation here is that it may be regarded as a lower limit for the region of interest; as Ulmer (1996) noted: "...However, the lines appear to be strongly correlated, and the number of expected unresolved pairs (with $\Delta v < 230$ km s$^{-1}$) is at least as large as the total number of resolved pairs with $230$ km s$^{-1} < \Delta v < 460$ km s$^{-1}$." This is certainly to be expected if clouds are physically associated with galaxies, since we confidently know that correlations of the known galactic population were smaller in the past. Since the large galaxy surveys of our time have become available, such investigations were performed several times (Infante & Pritchet 1992; Bernstein et al. 1994) with clear result: amplitude of the small-scale clustering increased by a factor of $\sim 2$ from the $z = 0.3$ epoch to the present epoch ($z < 0.1$). It should be emphasized that the obstacles in precise quantification of this effect are enormous, as discussed in detail in the study of Bernstein et al. (1994). Also, but less significantly, the theoretical work on N-body simulations (e.g. Yoshii, Peterson & Takahara 1993) came to the same conclusion about the general trend of the galaxy autocorrelation evolution. Thus, increased clustering of the Lyo absorbers may be better understood in framework of the same physical processes which govern the evolution of clustering of normal, luminous galaxies. The same general trend of increasing clustering with decreasing redshift is indicated by the data on Lyo forest in the HDF-S (Savaglio et al. 1999).

Additional argument in favor of this simple picture comes from considerations of influence of the absorbing cloud size on the correlation amplitudes. As correctly pointed out by Cristiani et al. (1997), a spatial correlation function convolved with velocity dispersion produces a correlation function in the velocity space similar to what is observed if a cloud sizes of $\sim 7.5$ h$^{-1}$ kpc irrespectively of redshift are assumed. We propose that this is quite realistic situation, and that realistic velocity dispersions required, or even smaller sizes, quite in accordance, for example, with the sizes obtained by the two-phase gas halo models of Mo (1994) and Mo & Miralda-Escudé (1996), Chiba & Nath (1997) or Miyahata & Ikeuchi (1995). Such clouds, having total masses $\sim 10^7 M_\odot$ are similar to progenitors of the present-day globular clusters. It is indicative that a decrease in the dominant velocity dispersion scale, which is allowed by all available empirical data (both from autocorrelation measurements and investigations of close pairs of lines of sight) will result in decrease in sizes of individual contiguous clouds.

4 DISCUSSION

This simple picture is what is generally expected from clouds residing in haloes dominated by dark matter, which are plausible physical candidates for our points around which absorbers are clustered with amplitude $f(v)$. In physical terms, the dependence of absorbing column density on distance from the center of an $L_B$ galaxy (Chen et al. 1998)

$$\log\left(\frac{N_H}{10^{20} \text{cm}^{-2}}\right) = -5.33 \log\left(\frac{\rho}{10 \text{ kpc}}\right) + 2.19 \log\left(\frac{L_B}{L_B^\ast}\right) + 1.09,$$

implies that strong absorption will be seen only near the halo center. It is straightforward to conclude that these strong and rare absorption lines have a relatively large probability of having weaker companion lines originating in the same halo, i.e. within the galaxy velocity dispersion. Therefore, overall clustering strength is expected to increase with column density. These absorption sites can be classical haloes of luminous galaxies or minihaloes (e.g. Meiksin 1994; Rauch 1998). Hypothesis that at least a fraction of Lyo clouds is located in extended haloes of luminous galaxies has found very strong support in low-redshift coincident studies (Lanzetta 2000 RAS, MNRAS 000, 000–000).
et al. 1996; Chen et al. 1998). In other words, the results of the present small-scale clustering analysis presented support the general subclass of models with dark matter-dominated gravitational confinement. The theoretical basis of such models is given in important works of Mo (1994) and Mo & Miralda-Escudé (1996), where the strongly physically motivated two-phase gaseous halo model has been developed in some detail. It is not clear at present whether some variant of Black’s (1981) classic self-gravitating confinement can also be cast in form which will satisfy the TPCF constraints, but it does not seem very promising. Contrariwise, the theories of origin of the Lyo forest which link the absorption to larger systems, i.e. clusters or superclusters (Oort 1981; Doroshkevich 1984) are in clear disagreement with these correlation measurements, due to much higher velocity dispersion of such structures. The same applies, as correctly noted by Srianand (1996), to the theories involving explosion-type processes (Ozernoy & Chernomordik 1978; Chernomordik & Ozernoy 1983; Vishniac & Bost 1987). On the other hand, strong anticorrelation between low-z Lyo equivalent widths (i.e. H I column densities) and galaxy impact parameter in absorption-selected galaxy sample of Chen et al. (1998), indicates that these objects share intragalactic velocity dispersions (i.e. the same velocity scales as discussed here). It is difficult, however, to distinguish between models with extended gaseous haloes and huge disks of Maloney (1992). It should be mentioned that York et al. (1986) have argued that there are large hydrodynamic velocities observed in absorption line systems which are similar to those seen in lines of sight through galaxies with active star formation. Along the same line of thought one should consider the finding of the HST Key Project (e.g. Boksenberg 1995) showing that the line density of Lyo absorption systems is greater by nearly an order of magnitude in the vicinity of metal-line systems (which are believed to originate in haloes of normal galaxies). In the framework of our toy model, this could be interpreted as an observational justification for neglecting ϕ(r) outside the range spanned by intragalactic velocities (0 − 250 km s−1). In general, the conclusion that the redshift dependence of the correlation function amplitudes can discriminate between various models of Lyo clouds has important and far-reaching consequences.

Parenthetically, the lack of power in the Lyo absorption line TPCF amplitudes at larger scales in comparison with the TPCF of local galaxies need not, along the general proposition of Dekel (1982), necessarily be understood as indication for physical difference of absorber and galaxy populations. Instead, one may follow the suggestion of Fang (1991) whose results indicate that a biased clustering in the universe simply has not occurred yet at z ≈ 2 on large (co-moving) scales. We should keep in mind that absence of large-scale clustering in the conventional Lyo forest samples has been based mainly on surveys of high-z absorption lines, usually with (z) ≥ 2. Only large Lyo forest surveys at intermediate and small redshift, likely to be available in the near future, will be capable of definitely solving the puzzle.

We conclude that at this level of accuracy of the TPCF measurements, a simple model with large and constant small-scale clustering is able to account for available observational evidence. Empirically well known galactic velocity dispersion seems to be capable of entirely explaining observed small-scale clustering properties of Lyo clouds, in agreement with the Occam’s razor. Much further theoretical work is certainly necessary in order to elaborate the details of the galactic halo model for Lyo clouds. However, the fact that this model is naturally arising in a compelling theoretical picture such as the halo cloud model is quite remarkable.

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REFERENCES

Barcons, X., & Webb, J. K. 1990, MNRAS, 244, 30p
Barcons, X., & Webb, J. K. 1991, MNRAS, 253, 207
Bernstein, G. M., Tyson, J. A., Brown, W. R., & Jarvis, J. F. 1994, ApJ, 426, 516
Binney, J., & Tremaine, S. 1987, Galactic dynamics (Princeton: Princeton University Press)
Black, J. H. 1981, MNRAS, 197, 553
Boksenberg, A. 1995, in QSO Absorption Lines, ed. G. Meylan (Berlin: Springer), 253
Carbone, V., & Savaglio, S. 1996, MNRAS, 282, 868
Cen, R., & Simcoe, R. A 1997, ApJ, 483, 8
Chen, H.-W., Lanzetta, K. M., Webb, J. K., & Barcons, X. 1998, ApJ, 498, 77
Chernomordik, V. V. 1995, ApJ, 440, 431
Chernomordik, V. V., & Ozernoy, L. M. 1983, Nature, 303, 153
Chiba, M., & Nath, B. B. 1997, ApJ, 483, 638
Cowie, L. L., Songaila, A., Kim, T.-S., & Hu, E. M. 1995, AJ, 109, 1522
Cristiani, S., D’Odorico, S., D’Odorico, V., Fontana, A., Giallongo, E., & Savaglio, S. 1997, MNRAS, 285, 209
Crotts, A. P. S. 1989, ApJ, 336, 550
Dekel, A. 1982, ApJ, 261, L13
Doroshkevich, A. G. 1984, AZh, 61, 218
Elowitz, R. M., Green, R. F., & Impey, C. D. 1995, ApJ, 440, 458
Fang, L. Z. 1991, A & A, 244, 1
Fardal, M. A., & Shull, J. M. 1993, ApJ, 415, 524
Fernández-Soto, A., Lanzetta, K. M., Barcons, X., Carswell, R. F., Webb, J. K., & Yahil, A. 1996, ApJ, 460, L85
Gnedin, N. Y., & Hui, L. 1996, ApJ, 472, L73
Heisler, J., Hogan, C. J., & White, S. D. M. 1989, ApJ, 347, 52
Hu, E. M., Kim, T.-S., Cowie, L. L., & Songaila, A. 1995, AJ, 110, 1526
Infante, L., & Pritchet, C. J. 1992, ApJS, 83, 237
Jannuzi, B. T. 1997, in Structure and Evolution of the Inter-galactic Medium from QSO Absorption Line Systems, ed. P. Petitjean & S. Charlot (Paris: Edition Frontières), 93
Jannuzi, B. T., et al. 1998, ApJS, 118, 1
Kim, T.-S., Hu, E. M., Cowie, L. L., & Songaila, A. 1997, AJ, 114, 1
Lanzetta, K. M., Webb, J. K., & Barcons, X. 1996, ApJ, 456, L17
Liu, X. D., & Jones, B. J. T. 1990, MNRAS, 242, 678
Lu, L., Sargent, W. L. W., Wombol, D. S., & Masahide, T.-H. 1996, ApJ, 472, 509
Maloney, P. 1992, ApJ, 398, L89
Meiksin, A. 1994, ApJ, 431, 109
Meiksin, A., & Bouchet, F. R. 1995, ApJ, 448, L85
Miyahata, K., & Ikeuchi, S. 1995, PASJ, 47, L37
Mo, H. J. 1994, MNRAS, 269, L49
Mo, H. J., & Miralda-Escudé, J. 1996, ApJ, 469, 589
Mo, H. J., Xia, X. Y., Deng, Z. G., Boerner, G., & Fang, L. Z. 1992, A & A, 256, L23
Muecket, J. P., & Mueller, V. 1987, Ap & SS, 139, 163
Oort, H. J. 1981, A & A, 94, 359
Ostriker, J. P., Bajtlik, S., & Duncan, R. C. 1988, ApJ, 327, L35
Ozernoy, L. M., & Chernomordik, V. V. 1978, Sov. Astron. 22, 141
Pando, J., & Fang, L.-Z. 1996, ApJ, 459, 1
Rauch, M., Carswell, R. F., Chaffee, F. H., Foltz, C. B., Webb, J. K., Weymann, R. J., Bechtold, J., & Green, R. F. 1992, ApJ, 390, 387
Rauch, M. 1998, ARAA, 36, 267
Salmon, J., & Hogan, C. 1986, MNRAS, 221, 93
Sargent, W. L. W., Young, P. J., Boksenberg, A., & Tytler, D. 1980, ApJS, 42, 41
Savaglio, S. et al. 1999, ApJ, 515, L5
Srianand, R. 1996, ApJ, 462, 68
Srianand, R., & Khare, P. 1994, MNRAS, 271, 81
Ulmer, A. 1996, ApJ, 473, 110
Vishniac, E. T., & Bust, G. S. 1987, ApJ, 319, 14
Webb, J. K. 1987, in Observational Cosmology, ed. A. Hewitt, G. Burbidge, & L. Z. Fang (Dordrecht: Reidel/Kluwer), p. 803
Webb, J. K., & Barcons, X., 1991, MNRAS, 250, 270
Weymann, R. J., et al. 1998, ApJ, 506, 1
White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341
York, D. G., Dopita, M., Green, R. & Bechtold, J. 1986, ApJ, 311, 610
Yoshii, Y., Peterson, B. A., & Takahara, F. 1993, ApJ, 414, 431