PROPERTIES OF THE LYMAN ALPHA CLOUDS FROM NON-EQUILIBRIUM PHOTOIONIZATION MODELS

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\begin{abstract}
We investigate the thermal and ionization history of Ly\(\alpha\) clouds photoionized by a time-dependent UV background, including nonequilibrium effects. The results show that it is possible to obtain temperatures as low as \(T \sim 15000\) K (or, equivalently, Doppler parameters \(b \sim 15\) \(\text{km s}^{-1}\)) at \(z = 3\) for cloud total densities \(n \sim 10^{-4}\) \(\text{cm}^{-3}\), if (i) the reionization epoch occurred at \(z \sim 10\), and (ii) the UV background has a factor 70–100 decrease at the HeII edge. A trend towards smaller \(b\) with increasing redshift is present in the redshift interval \(z = 1–5\). Higher densities lead to higher values of \(b\) and smaller hydrogen correction factors, \(n_{\text{HII}}/n_{\text{HI}}\). The correction factors for helium are also given. For a hydrogen column density \(N_{\text{HI}} = 3 \times 10^{14}\) \(\text{cm}^{-2}\), cloud sizes are larger than 100 kpc, consistent with recent observations of quasar pairs. Pressure confined models, instead, yield implausibly low cloud densities at low redshift, and too small sizes at intermediate redshift. The implications of the model are confronted with the available observational data.
\end{abstract}

\section{Introduction}

The study of the Ly\(\alpha\) absorbers seen in quasar spectra shortward of the quasar Ly\(\alpha\) emission has a considerable cosmological relevance as a probe of the physical properties of the neutral gas phase of the baryonic component of the Universe.

The optically thin Ly\(\alpha\) lines are usually associated to highly ionized clouds \((n_{\text{HI}}/n_{\text{HII}} \sim 10^3)\) in photoionization equilibrium with the general UV ionizing background (UVB) produced by quasars. The clouds may reside in the intergalactic space between galaxies or be associated with the big halos surrounding high redshift galaxies (Bahcall & Spitzer 1969; Sargent et al. 1980; Lanzetta et al. 1994).

The knowledge of the physical and cosmological properties of the Ly\(\alpha\) absorbers relies on a few parameters (redshift, column density, Doppler width) which can be derived from the line-profile fitting of (often blended) absorption features.

The column density distribution is a double power-law with a break at log \(N_{\text{HI}} = 14\) below which the slope is \(\beta_I \sim 1.4\). Above the break the slope is steeper, \(\beta_s \sim 1.8\) (Giallongo et al. 1996).

High resolution data taken at resolution \(R \sim 30000\) seem to indicate typical Doppler values of the order of \(b \sim 23 – 25\) \(\text{km s}^{-1}\) corresponding to cloud temperatures \(T \sim 32000 – 38000\) K (Cristiani et al. 1995, Hu et al. 1995, Giallongo et al. 1996).

It is important to note that narrow absorption lines with \(b \lesssim 20\) \(\text{km s}^{-1}\) have been observed in high resolution Ly\(\alpha\) samples. Chaffee et al. (1983) first noted that a line in their spectrum at resolution \(\sim 12\) \(\text{km s}^{-1}\) was surprisingly narrow with \(b \sim 15\) \(\text{km s}^{-1}\). More recent echelle data with variable signal-to-noise ratios reveal a non negligible fraction of narrow lines with Doppler parameter in the range \(10 < b < 20\) \(\text{km s}^{-1}\). The few lines \((\sim 1\%)\) with \(b \lesssim 10\) \(\text{km s}^{-1}\) present in the spectra have been often identified as metal-lines associated with heavy element systems (e.g. Rauch et al. 1993, Hu et al. 1995).

It is difficult to derive the intrinsic fraction of narrow lines with \(b \sim 15 – 20\) \(\text{km s}^{-1}\) since it depends on the S/N ratio, intrinsic blending of the lines, and resolution of the various spectra and on the fitting procedure adopted. These fractions range from 10% to 20% of the lines with log \(N_{\text{HI}} \gtrsim 12.8\) (Carswell et al. 1991; Rauch et al. 1993; Cristiani et al. 1995; Hu et al. 1995; Tytler 1995; Giallongo et al. 1996).

In any case, reconciling temperatures as low as \(T \sim 15000\) K with sizes along the L.o.s. greater than 30-50 kpc for the Ly\(\alpha\) clouds proves to be a difficult challenge. If the clouds are assumed in photoionization and thermal equilibrium with a power-law UV background produced by quasars at \(z = 2 – 4\), then temperatures \(T < 30000\) K could only be obtained increasing the hydrogen volume density to \(n_H > 10^{-3}\) \(\text{cm}^{-3}\). As a consequence, cloud sizes along
the line of sight drop down to $S_d < 100$ pc, as outlined by Chaffee et al. (1983), Pettini et al. (1990), and Donahue & Shull (1991).

Besides, a growing number of Lyα forest observations in quasar pairs suggest large transverse sizes of the clouds. Foltz et al. (1984) derived a lower limit in the range $5 - 25 h_{50}^{-1}$ kpc for the gravitational lensed pair Q2345+0007, while Smee et al. (1992) gave lower limits in the range $12 - 50 h_{50}^{-1}$ kpc for the QSO pair UM673. Recent measures by Bechtold et al. (1994) give larger values with a 90% lower limit $80 h_{50}^{-1}$ kpc at $z = 1.8$ for the diameters of spherical clouds. Smette et al. (1995) find a $2\sigma$ lower limit of $100 h_{50}^{-1}$ kpc for the diameter of spherical clouds at $z \sim 2$.

Given the implied low densities, radiative recombination can not be the main cooling agent for clouds with $T < 20000$ K. Duncan, Vishniac & Ostriker (1991) proposed adiabatic cooling due to cloud expansion against the external pressure of a diffuse but hot ($T > 10^5$ K) intergalactic medium. They obtained cloud temperatures $T \sim 15000$ K with sizes $\sim 20$ kpc. However, their calculations are based on the assumption of ionization equilibrium, and neglect heating from helium photoionization, which increases the cloud temperature by a factor 1.8.

Giallongo & Petitjean (1994) (GP) stressed the importance of the inverse Compton cooling on the CMBR, and of a steepening of the ionizing UV background at wavelengths shorter than the HeII edge. The combination of the two effects was shown to produce temperatures $T \sim 22000$ K with sizes up to $100 - 200$ kpc.

However, GP imposed both thermal and ionization equilibrium for clouds with densities $n_H \sim 10^{-4}$ cm$^{-3}$ at $z \sim 3$, an assumption which is only marginally consistent with the relevant timescales of the problem.

Models which include the effect of gravity have also been proposed (Petitjean et al. 1994; Meiksin 1994) in the context of the so called minihalo model (Rees 1986). Typical Doppler values $> 20$ km s$^{-1}$ are found together with cloud sizes $< 60$ kpc.

In the last period, several authors have studied the properties of the Lyα clouds in the general cosmological cold dark matter scenario (Hernquist et al. 1995; Zhang et al. 1995; Miralda-Escudé et al. 1995).

Although these models follow the formation and evolution of the Lyα clouds in a dynamical scenario, the treatment of photoionization is only approximate either because of the assumption of ionization equilibrium or because of the uniform ionizing background adopted with fixed initial conditions.

It is important to investigate time dependent photoionization models for the Lyα clouds for the following reasons: (i) the UVB produced by quasars has a strong dependence on redshift; (ii) the inverse Compton cooling time, $t_c$, is longer than the Hubble time, $t_H$, at the typical redshifts at which Lyα clouds are observed: $t_c/t_H \sim 40(1 + z)^{-2.5}$ (GP).

The aim of this study is to investigate in detail the thermal and ionization history of the clouds through a nonequilibrium photoionization model. This simple model allows us to explore the ionization state of the cloud as a function of a time-dependent UV background with different reionization epochs and with different shapes in frequency near the HeII edge.

Our results show that it is possible to obtain temperatures as low as $T \sim 15000$ K, for cloud total densities $n \sim 10^{-3}$ cm$^{-3}$ if the reionization epoch occurred at $z_i \gtrsim 10$ and if the UV background has a factor 70 – 100 decrease at the HeII edge.

## 2 PHOTOIONIZATION MODEL

The equations governing the thermal and ionization evolution of a Lyα cloud immersed in an isotropic ionizing background of intensity $I_\nu$ are (see Ferrara & Field 1994 for details):

$$\frac{d}{dt} n_{X,i+1} = \gamma_{\nu}(X^i) + \gamma_c(X^i, T)n_{X^i} n_e - n_{X,i+1} n_e \alpha(X^i, T),$$

$$\frac{k}{(\gamma - 1)} \frac{d}{dt} \left[ \sum_X \frac{h_X}{\mu_{X,i}} \right] = -\frac{1}{n} \mathcal{L}(X^i) + \frac{p}{n^2} \frac{dn}{dt}.$$  

The gas is assumed of primordial composition with a helium abundance equal to $n_{He} = 0.1 n_H$ and total number density $n$; even if metals are present, they do not affect the temperature very much provided the ionization level is high, as the one found here.

We consider the evolution of the following species: $H^0, H^+, He^0, He^+, He^{++}$, and electrons. The symbol $X = H, He$ denotes the element considered, and $i$ its state of ionization; obviously, $i = 0$ for hydrogen, and $i = 0, 1$ for helium; $n_e$ is the electron density, $\gamma$ is the specific heat ratio assumed to be constant and equal to $5/3$.

The photoionization rate $\gamma_{\nu}$ is given by

$$\gamma_{\nu}(X^i) = \int_{\nu L_X}^{\infty} \frac{J_{\nu}}{h\nu} \sigma_{\nu}(X^i) d\nu \left[ 1 + \phi(X^i) \right]$$

where $J_{\nu}$ is the first moment of the field, $\nu L_X$ indicates the ionization limit for each species, $\sigma$ is the photoionization cross section, $\phi$ is the secondary ionization rate, $\gamma_c$ is the collisional ionization coefficient, and $\alpha$ is the total recombination coefficient. We have adopted the “on the spot” approximation in which the diffuse field photons are supposed to be absorbed close to the point where they have been generated.

The energy equation (2.2) governs the evolution of the gas temperature $T$. We have used the following notation: $h_X = n_X/n$ is the relative abundance of the element $X$; $\sigma_{X,i+1} = n_X^{i+1}/n_X$ is the fractional density of the ionization state $i+1$ of the element $X$; $\mu_X = (\sum_{i=0}^{i=1} \gamma_{\nu}(X^i) d\nu - \sum_X \Lambda(X^i)$. The function $\mathcal{L}$ represents the net cooling rate per unit volume and is given by the difference between photoionization heating and radiative cooling:

$$\mathcal{L}(X^i) = \sum_i \sum_X n(X^i) \int_{\nu L_X}^{\infty} \frac{J_{\nu}}{h\nu} h[\nu - \nu L_X] \sigma_{\nu}(X^i) d\nu - \sum_X \Lambda(X^i).$$

The following processes have been included in the calculation of the cooling function: (i) free-free from all ions; (ii) H and He recombinations; (iii) electron impact ionization of H and He; (iv) electron impact excitation of H and He (n=2,3,4 triplets); (v) He dielectronic recombination. At
high temperatures or early epochs inverse Compton cooling on the CMWB photons is important and it has been included as in Ikeuchi & Ostriker (1986).

We mostly concentrate on constant cloud total density cases, (i.e., \(dn/dt = 0\) in eq. [2.2]); in addition, we also explore cases in which Lyα clouds are taken to be in pressure equilibrium with (and hence confined by) the surrounding IGM. To this aim, it is useful to write eq. (2.2) as follows:

\[
\frac{\gamma}{(\gamma - 1)} \frac{d}{dt} \left[ T \sum_X \frac{h_X}{\mu_{X,i}} \right] = -\frac{1}{n} \mathcal{L}(X^i) + \frac{kT}{p} \sum_X \frac{h_X}{\mu_{X,i}} \frac{dp_t}{dt},
\]

where \(p_t(z)\) is the pressure of the IGM, which is a prescribed function of the redshift \(z\). Ikeuchi & Ostriker (1986) (and more recently Shapiro 1995) have studied in detail the thermal history of the IGM from the era of the reheating to the present; they conclude that the most plausible scenario requires that both photoionization and bulk mechanical heating (i.e. shocks) contribute to the heating. Ikeuchi & Ostriker show that, if the reionization occurred at \(z_i = 10\) - for example - the initial evolution of the IGM is practically isothermal, \(p_t \propto (1 + z)^3\), and the IGM enters the adiabatic expansion phase, \(p_t \propto (1 + z)^3\), at \(z \lesssim 4\). As for the local value of the pressure, we take \(p_t(0) = 10^{-2}\) cm\(^{-3}\) K; we will use the cosmology \(\Omega = 1\) and \(h_{50} = 1\).

The problem is completely specified once the evolution of the UVB field is assigned together with the initial conditions (the latter are discussed below). We have assumed an evolving UVB following Madau (1991) and Meiksin & Madau (1993) model. The intensity of the UVB at the Lyman limit, \(J_{LL}\), evolves as \((1 + z)^3\) for \(z < 2\); it is approximately constant, i.e. \(\propto (1 + z)^{1/4}\), in the range \(2 \leq z \leq 3\), and it declines as \(\propto \exp[-0.69(z - 3)]\) for \(z > 3\).

We assume a normalization value \(J_{LL} = 7 \times 10^{-22}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) Hz\(^{-1}\) at \(z = 2\), consistent with the average value \(J_{LL} = 5 \times 10^{-22}\) found from the proximity effect of a Lyα high resolution sample evaluated in the redshift range \(z = 1.7 - 4.1\) (Giallongo et al. 1996). A power-law spectrum with index \(\alpha = -1.5\) for the UVB has been adopted.

In some cases a factor 100 break has been introduced at 4 Ryd to simulate the HeII absorption trough, consistently with the detections of the HeII Lyα Gunn-Peterson effect which have provided an indirect evidence of a steepening at the HeI edge with a UVB ratio between the Lyman limit and the HeII edge \(S_L \sim 100\) (Jakobsen et al. 1994).

### Figure 1.
(a) Evolution of the Doppler parameter \(b\) (lower panel) and of the hydrogen correction factor \(\chi_{H,1}\) (upper panel) for constant cloud density \(n = 10^{-4}\) cm\(^{-3}\) as a function of redshift for different initial conditions (see text). The initial conditions are \(z_i = 7, 10\) and \(T_i = 10^4, 10^5\) K. Points refer to \(b\) obtained assuming ionization and thermal equilibrium for comparison assuming the same UVB. Solid lines indicate cases with \(B = 1\) (no break); dotted lines indicate cases with \(B = 100\). The corresponding temperature scale in the lower panel is shown on the right axis. (b) As Fig. 1a, with initial conditions \(z_i = 7\) and \(T_i = 10^4\) K, \(B = 1\) for different values of the density: \(n = 10^{-3}\) cm\(^{-3}\) (solid), \(n = 10^{-4}\) cm\(^{-3}\) (dotted line), \(n = 10^{-5}\) cm\(^{-3}\) (long-dashed).

The gas is supposed to be mostly neutral at \(z = z_i\); different assumptions produce slight changes only for redshifts outside the currently observable range. At \(z = 10\) the Compton cooling time is so short that there are no relevant differences between the two different \(T_i\).

Fig. 1a shows the thermal and ionization evolution of a Lyα cloud as described by the Doppler parameter, \(b = (2kT/m_H)^{1/2}\) and the hydrogen correction factor, \(\chi_{H,1} = n_{HII}/n_{H} = x_{H,1}/(1 - x_{H,1})\). The Doppler parameter evolves strongly as a function of redshift and, indepen-
dently of $T_i$ and $z_i$, reaches a maximum value $b \simeq 28$ km s$^{-1}$ at about $z = 1.2$ for $B = 1$, i.e., no HeII break; the memory of the initial conditions is completely washed away already at $z \simeq 2$, for both cases $B = 1$ and $B = 100$. The temperature peak is due to the lower efficiency of the Compton cooling which decreases as $(1 + z)^4$; for $z \lesssim 1.2$ this effect is overwhelmed by the decrease of the UVB, and hence of the photoionization heating. The peak position also lags behind an analogous maximum of $\chi_{H,1}$ (see below) since the decrease in the photoionization heating is initially compensated by a larger neutral fraction.

The cases $B = 100$ look qualitatively similar to the $B = 1$ ones, but they show a general tendency towards lower temperatures, with a minimum value $b \simeq 13$ km s$^{-1}$ attained at $z = 6 - 7$, with $z_i = 10$. It is worth mentioning, though, that even at $z = 3$ typical $b$ values are $16 - 18$ km s$^{-1}$, to be compared with $b \simeq 23$ km s$^{-1}$ for the no break case.

The hydrogen correction factor $\chi_{H,1}$ traces to a good extent the evolution of the UVB, peaking at $z = 2$; the range of variation of $\chi_{H,1}$ is $3000 - 10^5$. The evolution is rather insensitive to $z_i$ and $T_i$, the different curves converging as early as $z \simeq 5$. A $B = 100$ break reduces $\chi_{H,1}$ by $\sim 35\%$ around the maximum ($z = 2$).

We have also explored the cases $n = 10^{-3}$ cm$^{-3}$ and $n = 10^{-4.5}$ cm$^{-3}$ with initial conditions $z_i = 7$ and $B = 1$; the corresponding evolutionary curves are shown in Fig. 1b. The behavior $\chi_{H,1}$ is qualitatively the same as above; in particular the value of the maximum increases almost linearly with $n$. The Doppler parameters are lower that for the standard $n = 10^{-4}$ cm$^{-3}$ case both for $n = 10^{-3}$ cm$^{-3}$ and for $n = 10^{-4.5}$ cm$^{-3}$ (this is due to a transition from Compton cooling dominated losses at low $n$ to recombination dominated cooling at higher $n$). In addition, the maximum of the $b$ curve shifts towards lower redshifts as the density is decreased.

In general, we can define correction factors for helium in analogy to the hydrogen one as $\chi_{He,i+1} = n_{He,i+1}/n_{HI} = \frac{b_{He,x_{He,i+1}}}{b_{H}(1 - x_{H,1})}$ (notice the definition relative to neutral hydrogen). Fig. 2 shows the behavior of the helium correction factors as a function of redshift. The most relevant feature is the change in the evolution of the HeII fraction from the cases $B = 1$ to the cases $B = 100$. For $B = 1$ and $z < 5$, $\chi_{He,1}$ has an almost constant low value $\sim 20$, i.e., most of the He is in the doubly ionized state. As $B$ is increased to 100, $\chi_{He,1}$ develops a maximum around $z = 3$ of about 4000, a value similar to that of $\chi_{He,2}$ in the same redshift interval. Thus the ratio of the two correction factors provides a very sensitive measure (and test) of the 4 Ryd breaking.

The previous results allow to compute the Ly$\alpha$ cloud sizes along the l.o.s. $S_i = N_{HI}(1 + \chi_{H,1})/n$ at any given redshift, as illustrated by Fig. 3. Typical sizes of the clouds are several kpc, ranging from a minimum of about 5 kpc for $N_{HI} = 10^{19}$ cm$^{-2}$ to 100-120 kpc for $N_{HI} = 3 \times 10^{21}$ cm$^{-2}$ in the redshift interval 2-3. Given the higher neutral fraction found in models with $B = 100$, sizes are a factor $\sim 1.5$ smaller. Apart from $B$, the sizes are quite insensitive to the initial conditions. Locally ($z = 0$), clouds with $N_{HI} < 3 \times 10^{18}$ cm$^{-3}$ are predicted to have sizes not exceeding 5 kpc.

Finally, models in which Ly$\alpha$ clouds are assumed to be in pressure equilibrium with the IGM, according to eq. (2.3), are presented in Fig. 4. The temperature of the clouds is now a monotonically increasing function of time, as the cooling reduction caused by the density decrease dominates the opposite effect due to the decrease of the photoionization energy input. At $z = 3$, $b = 23 - 25$ km s$^{-1}$, depending on $B$. We point out that these results depend on the particular assumption made for the thermal history of the IGM, following Ostriker & Ikeuchi (1986); deviations from these values may produce quantitative changes in the determination of $b$. The same behavior is shown by $\chi_{H,1}$, which reaches very high values $(\sim 3 \times 10^6)$ at $z = 0$. The total density $n$ of the cloud drops very rapidly from the initial value $n_i \simeq 10^{-2}$ cm$^{-3}$ to an extremely low value $\simeq 10^{-7}$ cm$^{-3}$ at $z = 0$ (essentially the IGM density). As a consequence, sizes are implausibly large, or, stated in a different way, the clouds would dissolve rapidly below $z \sim 2$. At intermediate redshifts, pressure confined models yield essentially the same $b$ values as the constant density, $B = 1$ cases (but higher than $B = 100$ ones):

however, correction factors (and thus sizes) are typically one order of magnitude smaller. Thus, low-$z$ Ly$\alpha$ clouds observations can be used to put strong constraints on pressure confinement models.

4 DISCUSSION AND IMPLICATIONS

We first compare our time-dependent results with the ones obtained by GP who assumed thermal and ionization equilibrium. GP used a value of $J_{LL} = 10^{-21}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$, a value corresponding to $z = 2.25$ for the presently adopted $J_\nu(z)$. At that redshift, the cloud temperature (see
Figure 3. Cloud sizes $S_\parallel$ for constant cloud density $n = 10^{-4} \text{ cm}^{-3}$ as a function of redshift for initial conditions $z_i = 10$, $T_i = 10^4 \text{ K}$. Solid lines correspond to $B = 1$ (no break); dotted lines correspond to $B = 100$. Three different hydrogen column densities $N_{HI} = 10^{13}, 10^{14}, 3 \times 10^{14} \text{ cm}^{-2}$ are shown for each case.

Fig. 1a) is $T \simeq 3 \times 10^4 \text{ K}$ for $B = 1$, and $T \simeq 2 \times 10^4 \text{ K}$ for $B = 100$, to be compared with the analogous values obtained by GP (see their Fig. 1), $T \simeq 4.7 \times 10^4 \text{ K}$ for $B = 1$, and $T \simeq 3 \times 10^4 \text{ K}$ for $B = 100$. We have plotted in Fig. 1a the values of $b$ obtained assuming ionization and thermal equilibrium for comparison assuming the same UVB. The reasons for the discrepancy are: (i) Compton losses on the CMWB strongly cool the clouds at high redshift; (ii) the UVB decreases exponentially for $z > 3$; and (iii) nonequilibrium effects. The sizes found by GP are about a factor 1.5 larger for the same $N_{HI}$ and $n$, thus implying a larger hydrogen correction factor. This is due to the enhanced collisional ionization produced by their higher temperature.

The bottom line of our study is that it is feasible to reconcile two apparently conflicting observed properties of the Lyα clouds, low temperatures and large sizes, basically with one assumption, i.e. the existence of a break in the UVB at the HeII edge. It is easy to show that Lyα clouds become optically thick to radiation above the HeII Lyman limit for a neutral hydrogen column density $N_{HI} = 6.3 \times 10^{17}/\chi_{He,1} \text{ cm}^{-2}$. For the calculated values of $\chi_{He,1} \sim 20$ ($B = 1$), Lyα clouds with $N_{HI} > 3 \times 10^{16} \text{ cm}^{-2}$ will substantially absorb the flux above 4 Ryd, thus enhancing the value of $\chi_{He,1}$ even further (see Fig. 2 for $B = 100$). This well-known (Miralda-Escude & Ostriker 1990, Shapiro 1995) nonlinear effect is thus responsible not only for the break, but also, given the reduced HeII ionizing flux, for a detectable HeII Gunn-Peterson effect (Jakobsen et al. 1994).

In addition, from our results we do expect the presence of a pronounced He II Lyα forest.

The issue about Doppler parameters and cloud sizes deserves some additional discussion. First it appears that $b$ values lower than about 15 km s$^{-1}$ cannot be reproduced by any of our nonequilibrium models. This agrees with the presence of a lower envelope of the $b$-distribution with a cut-off at $b_c \simeq 16 \text{ km s}^{-1}$ found by different investigators (Carswell et al. 1991, Rauch et al. 1992, 1993, Hu et al. 1995, Giallongo et al. 1996), disputing a previous claim by Pettini et al. (1990) of a lower value of $b_c$, probably affected by line selection and fitting procedure artifacts. Quite interestingly, we find also an upper limit $b \simeq 28 \text{ km s}^{-1}$, whereas the above studies have inferred $b$-values as high as 60 km s$^{-1}$. The most natural suggestion is that high-$b$ values can be unresolved blends of $b \simeq b_c$ lines (Rauch et al. 1992, Hu et al. 1995). However, in this case the two-point correlation function should display an increased amplitude on small scales, typically $\Delta v < 100 \text{ km s}^{-1}$. Some indirect support to this hypothesis is lent by Cristiani et al. 1995 and Meiksin & Bouchet (1995), who both found significant clustering on scales $\Delta v \geq 100 \text{ km s}^{-1}$. If blending is viable, departures from Maxwellian velocity distribution are expected (Kulkarni & Fall 1995). A different explanation, i.e. bulk motions, has been shown (Press & Rybicki 1993) to encounter apparently insurmountable difficulties. Alternatively, if a hot IGM does exist, temperatures of the order of a few $\times 10^5 \text{ K}$ could be generated in the interfaces between the IGM and

Figure 4. As Fig. 1a, but for the constant pressure case, and initial conditions $z_i = 7,10$, $T_i = 10^4 \text{ K}$. The dashed line in the upper panel is the total density, $n$, of the cloud. Solid lines correspond to $B = 1$ (no break); dotted lines correspond to $B = 100$. 

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the clouds by thermal conduction (Ferrara & Shchekinov 1996).

The cloud sizes $S_\parallel$ derived here for $n = 10^{-4}$ cm$^{-3}$, albeit larger than in previous models, are still smaller than the transverse ones, $S_\perp$, inferred either from lensed or paired quasars. Thus, unless cloud densities are smaller than $\sim 10^{-4}$ cm$^{-3}$, we are forced to conclude that clouds must be flattened, a conclusion shared by other investigators on different grounds (Rauch & Haehnelt 1995, Hu et al. 1995).

Dinshaw et al. (1994,1995) have provided very interesting evidence for the evolution of $S_\perp$: from their quasar pair experiments they obtain $S_\perp > 320h_{50}^{-1}$ kpc in $z = 0.5 - 0.9$ and $S_\perp > 80h_{50}^{-1}$ kpc at $z = 1.8$. From Fig. 3, independently of $N_{HI}$, the ratio $S_\parallel(1.8)/S_\parallel(0.5) = 5.6$, while the analogous ratio for $S_\perp$ is $\sim 0.25$. Although very speculative, this finding seems to suggest that the clouds evolve from an approximately round shape to a highly flattened one, reminiscent of a gravitational collapse, between $z \sim 2$ and $z \sim 1$.

REFERENCES

Bahcall, J. N. & Spitzer, L. 1969, ApJ, 166, L63
Bechtold, J., Crotts, A. P. S., Duncan, R. C, & Fang, Y. 1994, ApJ, 437, L83
Carswell, R. F., Lanzetta, K. M., Parnell, H. C., & Webb, J. K. 1991, ApJ, 371, 36
Chaffee, F.H. Jr., Weymann, R. J., Latham, D. W. & Strittmatter, P. A. 1983, ApJ, 267, 12
Cristiani, S., D’Odorico, S., Fontana, A., Giallongo, E. & Savaglio, S. 1995, MNRAS, 273, 1016
Dinshaw, N., Impey, C. D., Foltz, C. B., Weymann, R. J. & Chaffee, F. H. 1994, 437, L87
Dinshaw, N., Foltz, C. B., Impey, C. D., Weymann, R. J. & Morris, S. L. 1995, Nature, 373, 223
Donahue, M., & Shull, J. M. 1991, 383, 511
Duncan, R. C., Vishniac, E. T., & Ostriker, J. P. 1991, ApJ, 368, L1
Ferrara, A. & Field, G. B. 1994, ApJ, 423, 665
Ferrara, A. & Shchekinov, Y. 1996, ApJL, in press
Foltz, C. B., Weymann, R. J., Roser, H. J., & Chaffee, F. H., Jr. 1984, ApJ, 281, L1
Giallongo, E. & Petitjean, P. 1994, ApJ, 426, L61 (GP)
Giallongo, E., Cristiani, S., D’Odorico, S., Fontana, A., & Savaglio, S. 1996, ApJ, in press
Hernquist, L., Katz, N., Weinberg, D. H., Miralda-Escudé, J. 1996, ApJ, 457, L51
Hu, E. M., Kim, T., Cowie, L. L., & Songaila, A. 1995, AJ, 110, 1526
Jakobsen, P., Boksenberg, A., Deharveng, J. M., Greenfield, P., Jedrzejewski, R. & Paresce, F. 1994, Nature, 370, 35
Lanzetta, K. M., Bowen, D. V., Tytler, D., & Webb, J. K. 1994, ApJ, 442, 538
Ikeuchi, S. & Ostriker, J. P. 1986, ApJ, 301, 522
Kulkarni, V. P., & Fall, S. M. 1995, ApJ, 453, 65
Madau, P. 1991, ApJ, 376, L33
Meiksin, A. 1994, ApJ, 431, 109
Meiksin, A., & Madau, P. 1993, ApJ, 412, 34
Meiksin, A., & Bouchet, F. R. 1995, ApJ, 448, L85
Miralda-Escudé, J., Cen, R., Ostriker, J. P., & Rauch, M. 1995, submitted to ApJ
Pettini, M., Hunstead, R. W., Smith, L. J., & Mar, D. P. 1990, MNRAS, 246, 545
Press, W. H., & Rybicki, G. B. 1993, 418, 585
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., Carswell, R. F., Webb, J. K., & Weymann, R. J. 1993, MNRAS, 260, 589
Rauch, M., & Haehnelt, M. G. 1995, MNRAS, 275, L76
Rees, M. J. 1986 MNRAS, 218, 25P
Sargent, W. L. W., Young, P. J., Boksenberg, A. & Tytler, D. 1980, ApJS, 42, 41
Shapiro, P. R. 1995, in The Physics of the Interstellar and Intergalactic Medium, PASP Series, Vol. 80, eds. A. Ferrara, C. F. McKee, C. Heiles, P. R. Shapiro, (PASP: San Francisco), 55
Smette, A., et al. 1992, ApJ, 389, 39
Smette, A., Robertson, J. G., Shawer, P. A., Reimers, D., Wisotzki, L. & Köhler, Th. 1995, A&A Suppl., 113, 199
Tytler, D. et al. 1995, in QSO Absorption Lines, Springer, Ed. G. Meylan, 289.
Zhang, Yu, Anninos, P., Norman, M. L. 1995, ApJ, 453, L57
Figure 1b
Figure 2

Correlation Factors $X_{\rm H\alpha,1}$

$n = 10^{-4}\,\text{cm}^{-3}$
Figure 3
