Testing the Pressure-confined Lyα Cloud Model

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Introduction: The Lyα absorption line forest, seen in quasar spectra, is generally interpreted as being due to cosmologically distributed ‘clouds’ of primordial gas. Analyses of the observations (e.g. Rauch et al. 1992) reveal that the number distribution can be described by power laws: \( dN/dz \propto (1+z)^\gamma \) and \( dN/dN_{HI} \propto N_{HI}^\beta \), where \( N_{HI} \) is the HI column density. The typical values for power law indices range between \( 2 \leq \gamma \leq 2.6 \) and \( 1.7 \leq \beta \leq 1.9 \). One model postulates that the Lyα clouds are optically thin entities, photoionized by the background UV flux, \( J_\beta \propto (1+z)\delta \), and confined by an adiabatically evolving intercloud medium (ICM): \( P(z) \propto (1+z)\delta \). Analytic studies of this model suggest that the ensuing Lyα line statistics can account for the observations (in particular, the \( dN/dz \) and the \( dN/dN_{HI} \) distributions) if the cloud mass spectrum is a power law \( dN/dM \propto M^{-\delta} \), \( \delta \approx 1.9 \), and \( j \approx 4 \) (e.g. Ikeuchi & Ostriker 1986, IO). One of the simplifying assumptions incorporated into these studies is the existence of a large mass range for the clouds at all epochs, the validity of which is questionable.

Simulations: We investigate the pressure-confined model using a 1-D spherically symmetric hydrodynamical code to simulate cloud evolution over the epoch \( 1.8 \leq z \leq 6 \). This enables us to relax many of the assumptions incorporated in the analytic studies. We only consider clouds with masses \( 2.75 \leq \log(M/M_\odot) \leq 9.25 \). Clouds with larger masses are Jeans unstable and tend to collapse; they are not ‘pressure-confined’. The lower mass limit is chosen to ensure all clouds that can produce absorption features with equivalent widths \( W_\alpha \geq 0.2 \AA \) over the epoch \( 1.8 \leq z \leq 3.6 \) are considered. We calculate Voigt profiles from the model clouds at varying impact parameters and use the resulting absorption features to determine line-profile parameters (e.g. \( N_{HI} \), the rest-frame equivalent width \( W_\alpha \), and the Doppler parameter \( b \)). We construct synthetic samples of lines subject to similar selection criteria used to define a sample of \( \sim 400 \) observed lines (i.e. \( W_\alpha \geq 0.2 \AA \)). In this sense, the present study is unique: past theoretical studies have relied on column density thresholds. \( N_{HI} \), however, is a fitted parameter and is sometimes subject to large uncertainties. Line widths have been traditionally used to define observational samples as they are directly measurable. We compare the synthetic \( dN/dW_\alpha \), \( dN/dN_{HI} \) and \( dN/dz \) distributions against the observed trends. The synthetic results are normalized by demanding that the number of clouds with \( W_\alpha \geq 0.2 \AA \) be the same as observed. Apart from studying the properties of clouds immersed in \( j = 4 \) UV background, we also consider the possibility that the UV background is constant at the epoch of interest. For more details, see Williger & Babul (1992; WB).

Results: The redshift-integrated \( dN/dW_\alpha \) distributions for \( j = 0 \), \( 4 \) (\( \delta = 1.90 \)) are shown in Figure 1. Clearly, there is a shortage of model lines with \( W_\alpha > 0.3 \AA \), in comparison with the observations. The result is partly due to the fact that \( b \approx 22 \) km s\(^{-1}\) for simulated pressure-confined clouds (with a dispersion of approx. \( 1 \) km s\(^{-1}\)) — i.e. \( b \) is due to thermal velocities — while \( b \approx 35 \) km s\(^{-1}\) for the observed lines (with a dispersion of approx. \( 15 \) km s\(^{-1}\)). The lower \( b \) for the simulated clouds implies that these clouds require larger column densities than those associated with the observed lines in order to account for the observed \( dN/dW_\alpha \) distribution. The imposition of the upper mass limit for the pressure-confined clouds, however, restricts the column density range of the simulated clouds.

The \( dN/dN_{HI} \) distributions for the simulated and the observed clouds in the redshift range \( 2.6 \leq z \leq 2.8 \) (Figure 2) shows that although the two are consistent with each other for \( \log(N_{HI}) \leq 15.2 \), there are fewer model clouds with \( N_{HI} \) larger than observed. Note that the shortage is more severe for the \( j = 4 \) case as the UV background at \( z \approx 2.7 \) is more intense than in the \( j = 0 \) case and therefore the clouds are more highly ionized. We also show the “analytic” \( dN/dN_{HI} \), computed using the simple homologously-expanding pressure-confined cloud model of IO and the prescription of WB (e.g. we explicitly take into account the upper mass limit). This distribution cuts off at even a lower \( N_{HI} \) than the synthetic distribution; the simulations reveal that the more massive clouds tend not to expand homogenously and, consequently, develop non-uniform density profiles. Self-gravity also retards their expansion.

In Figure 3, we show the observed and the synthetic \( dN/dz \) distributions for clouds with \( W_\alpha \geq 0.2 \AA \); the \( dN/dz \) distribution for a subset of clouds with \( W_\alpha \geq 0.3 \AA \) is shown in Figure 4. For \( W_\alpha \geq 0.2 \AA \) sample, the synthetic results match the observations well. Neither the normalization (reflecting the discrepancy in
the $dN/dW_r$ distributions) nor the slope of the synthetic $dN/dz$ (the number of pressure-confined clouds decreases much too rapidly at low redshifts) matches the observations for the subset with $W_r \geq 0.3\AA$. The rapid decline in clouds with large equivalent widths towards lower redshifts is, once again, due to the upper mass limit for the clouds.

Conclusions: As a result of an upper limit to the mass of pressure-confined clouds and the “thermal” Doppler parameters, the equivalent width and column density distributions for spherical, pressure-confined clouds with a power-law mass spectrum fail to account for the observations. The upper mass limit is determined by nature of the evolution of both the ICM pressure and the UV background; in order to achieve an acceptable fit to the data, we require the ICM pressure to decrease as $P(z) \propto (1+z)^P$, $P > 5.8$ (WB). This is difficult to justify physically. Aspherical clouds, on the other hand, may allow the pressure-confined model to remain viable.


Fig. 1. $dM/dW_r$ of the observed clouds vs. the 2-integrated distribution of the model clouds. The $j = 0, 4$ cases for $\delta = 1.90$ are shown by solid, dashed lines respectively. The error bars indicate bin widths and 1$\sigma$ errors for the observations.

Fig. 2. Column density distribution of the observed clouds vs. models in the redshift range $2.6 < z < 2.8$. The various curves correspond to various analytic and synthetic results: $j = 0/j = 4$ synthetic (solid/dashed); $j = 0/j = 4$ analytic (dotted/dot-dashed). At high $N_{HI}$, the synthetic curves steepen before an abrupt cutoff. The cutoff is even lower for the analytic models.

Figs. 3-4. The observed vs. model redshift distribution of Lya clouds with $W_r \geq 0.2\AA$ (Fig. 3) and $W_r \geq 0.3\AA$ (Fig. 4). The various curves correspond to various analytic and synthetic results: $j = 0/j = 4$ synthetic (solid/dashed); $j = 0/j = 4$ analytic (dotted/dot-dashed). Although the synthetic curves fit the data for $W_r \geq 0.2\AA$, there are significant discrepancies in the slope and the normalization for $W_r \geq 0.3\AA$. The analytic fits are worse, except for $j = 4$, $W_r \geq 0.2\AA$. 

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