Explaining the Lyman-alpha forest

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Abstract. It is shown that many properties of Lyα forest absorbers can be derived using simple physical arguments. Analytical expressions are derived for the density and the size of an absorber as a function of its neutral hydrogen column density, which agree well with both observations and hydrodynamical simulations. An expression is presented to compute Ω_{IGM} from the observed column density distribution, independent of the overall shape of the absorbers. Application to the observed column density distribution shows that at high redshift most of the baryons are in the forest and suggests a simple interpretation for its shape and evolution.

1 Introduction

In the last decade semi-analytic models (e.g., [2]) and hydrodynamical simulations (see [3] for a recent review) have been used to show that cold dark matter models with a nearly scale-invariant spectrum of initial, adiabatic, Gaussian fluctuations are very successful in reproducing the large body of high-quality observations of the Lyα forest. The physical picture that has emerged is that the forest arises in a network of sheets, filaments, and halos, which give rise to absorption lines of progressively higher column densities. The low column density absorption lines ($N_{HI} < 10^{14.5}$ cm$^{-2}$ at $z \sim 3$), arise in a smoothly fluctuating intergalactic medium (IGM) of moderate overdensity ($\rho < 10 \langle \rho \rangle$), and contain most of the baryons in the universe. On large scales the gas traces the dark matter and observations of the Lyα forest can be used to study the large-scale distribution of matter, while on small scales hydrodynamical effects are important and the detailed line profiles can be used to reconstruct the thermal history of the IGM. In this contribution I will show that the modern picture of the forest can be derived directly from the observations using straightforward physical arguments, without making any assumptions about the presence of dark matter, the mechanism for structure formation or the precise cosmological model. This work is described in more detail in a recent publication [8].

2 Physics

Consider an (optically thin) self-gravitating gas cloud of arbitrary shape that is intersected by our line of sight to a background QSO. Let $n_H$ be the characteristic total hydrogen number density of the absorber, i.e., the density weighted
by the neutral hydrogen column density and let $L$ be the characteristic size of the absorber, i.e., the size over which the density is of order $n_H$.

Regardless of whether the cloud as a whole is in dynamical equilibrium, it will in general not be far from local hydrostatic equilibrium, i.e., $L \sim L_J$ where $L_J$ is the local Jeans length. If $L \ll L_J$, then the cloud will expand or evaporate and equilibrium will be restored on a sound-crossing time scale. If $L \gg L_J$, then the cloud is Jeans unstable and will fragment or shock and equilibrium will be restored on a dynamical time scale. Note that this argument breaks down if the relevant time scale is larger than the Hubble time, because in that case there simply has not been sufficient time to establish equilibrium.

Since $t_{\text{dyn}} \equiv (G \rho)^{-1/2}$ and $t_H \equiv H^{-1} \sim (G \langle \rho \rangle)^{-1/2}$ this is true for underdense absorbers. Such absorbers have sizes greater than the sound horizon and can be regarded as a “fluctuating Gunn-Peterson effect”. Systematic departures from local hydrostatic equilibrium ($L \ll L_J$) also occur in clouds confined by external pressure (but the large cloud sizes derived from observations of quasar pairs rule out the possibility that a significant fraction of the forest arises in pressure confined clouds [7]), and in rotationally supported clouds whose spin axis is nearly perpendicular to our sight line.

### 3 Results

Combining the condition of local hydrostatic equilibrium, $L \sim L_J$, with the expression for the neutral fraction in an optically thin plasma, $n_{\text{HI}}/n_H \approx 0.46 n_{\text{HI}} T_4^{-0.76} \Gamma_{12}^{-1}$ (where $T_4 \equiv T/10^4 \text{K}$ is the temperature and $\Gamma_{12} \equiv \Gamma/10^{-12} \text{s}^{-1}$ is the hydrogen photoionization rate), yields expressions for the density and size of an absorber as a function of its neutral hydrogen column density [8]:

$$N_{\text{HI}} \sim 2.7 \times 10^{13} \text{ cm}^{-2} \left( \frac{\rho}{\langle \rho \rangle} \right)^{3/2} \Gamma_{12}^{1/2} T_4^{0.26} \left( \frac{1 + z}{4} \right) \frac{\Omega_b h^2}{0.02} \frac{f_g}{0.16} \left( \frac{1}{2} \right)^{1/2}$$

$$L \sim 1.0 \times 10^2 \text{ kpc} \left( \frac{N_{\text{HI}}}{10^{14} \text{ cm}^{-2}} \right)^{-1/3} \left( \frac{\Omega_m}{0.16} \right)^{2/3}$$

where $f_g \approx \Omega_b/\Omega_m$ is the fraction of the mass in gas (excluding stars and molecules). From the line widths of the absorption lines it is known that the temperature is roughly consistent with that expected from photoionization heating, $T_4 \sim 1$. Studies of the proximity effect estimate $\Gamma_{12} \sim 1$ at $z \sim 3$ and $\Gamma_{12} \sim 10^{-1}$ at $z \sim 0$ (e.g., [8]).

The density - column density relation agrees with published results from hydrodynamical simulations to within a factor of a few, about as well as different simulations agree with each other. The sizes of the absorbers have not been investigated in detail with simulations, but equation 3 does agree with the sizes derived from observations of multiple sight lines (e.g., [9]).

Using equation 3 to compute the neutral fraction as a function of column density, we can compute $\Omega_{\text{IGM}}$, the contribution of the Lyα forest to the cosmic
baryon density, directly from the observed column density distribution:

$$\Omega_{\text{IGM}} \sim 2.2 \times 10^{-9} h^{-1/2} \left( \frac{f_g}{0.16} \right)^{1/3} T_4^{0.59} H(z) \frac{1}{H_0} (1 + z)^2 \int N_{HI}^{1/3} \frac{d^2 n}{dN_{HI} d\delta} \ dN_{HI}. \quad (3)$$

Figure 1a shows the observed column density distribution at \( z \sim 3 \) and the single power law fit of Hu et al. (1995) (dashed line). Integration of this column density distribution according to equation (3), using \((T_4, \Gamma_{12}, f_g, h, \Omega_m, \Omega_\Lambda) = (2.0, 1.0, 0.16, 0.65, 0.3, 0.7)\), yields \( \Omega_{\text{IGM}} h^2 \approx 0.015 \) for \( \log N_{HI} = 13.0 - 17.2 \), confirming that at high \( z \) most of the baryons are in the diffuse IGM.

Figure 1b shows the derived mass distribution, i.e., \( d\Omega_{\text{IGM}}/d\log(1 + \delta) \). The shape of the mass distribution clearly reflects the deviations from a single power law column density distribution and agrees reasonably well with the actual mass distribution in a hydrodynamical simulation (solid line), kindly provided by T. Theuns. The agreement becomes even more impressive if we compare with the distribution of gas that has a temperature \( \log T < 4.8 \) (dashed line), low enough for collisional ionization to be ineffective. This good agreement suggests that the observed structure in the IGM formed through gravitational instability in an expanding universe, as is the case in the simulation.

The shape of the mass distribution derived from the observations also suggests a simple physical interpretation for the deviations from the single power law in the observed column density distribution, whose origin was not yet understood. The steepening at \( N_{HI} \sim 10^{14.5} \ \text{cm}^{-2} \) reflects the fall-off in the density distribution due to the onset of rapid, non-linear collapse at \( \delta \sim 10 \). Finally, the flattening at \( N_{HI} \sim 10^{16} \ \text{cm}^{-2} \) can be attributed to the flattening of the density distribution at \( \delta \sim 10^2 \) due to the virialization of collapsed matter.

The evolution of the shape of the column density distribution can now also be explained. From \( z \sim 3 \) to \( z \sim 0 \), the slope of the column density distribution is found to steepen for \( N_{HI} \sim 10^{13-14} \ \text{cm}^{-2} \) and to flatten for \( N_{HI} \sim 10^{15-16} \ \text{cm}^{-2} \) (e.g., $[5]$). If gravitational instability is responsible for the shape of the gas density distribution, then this distribution will be similar at \( z \sim 0 \) and \( z \sim 3 \), provided it is expressed as a function of the density relative to the cosmic mean. Hence, the change in the slope of the column density distribution must mainly be due to the evolution of the function \( N_{HI}(\delta) \), which is determined by the expansion of the universe and the evolution of the ionizing background. Equation (3) shows that \( N_{HI} \propto (1 + z)^{9/2}/\Gamma \). The neutral hydrogen column density corresponding to a fixed density contrast is thus about a factor \( 5 \times 10^2 \Gamma(z = 0)/\Gamma(z = 3) \sim 5-50 \) lower at \( z \sim 0 \) than at \( z \sim 3 \), and this can account for the evolution in the observed distribution.

This work demonstrates that the main aspects of the physical picture of the Ly\( \alpha \) forest, including the facts that the absorbers are extended, of low overdensity, and contain a large fraction of the baryons, can all be derived directly from the observations using straightforward analytical arguments, with-
out making assumptions about the presence of dark matter, the mechanism for structure formation, or the precise cosmology. Although this analysis is essentially model-independent, the shape of the derived mass distribution strongly suggests that gravitational instability in an expanding universe is responsible for the distribution of matter in the IGM, thus lending credence to the use of ab-initio hydrodynamical simulations to investigate the detailed properties of the forest and their dependence on the parameters of the models.

References

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