Hubble Flow Broadening of the Lyman-alpha Forest and its Implications[1]

David H. Weinberg[1], Lars Hernquist[2], Neal Katz[3], Rupert Croft[1], Jordi Miralda-Escudé[4]

[1] *Ohio State University, Dept. of Astronomy, Columbus, OH 43210*
[2] *University of California, Lick Observatory, Santa Cruz, CA 95064*
[3] *University of Massachusetts, Dept. of Physics and Astronomy, Amherst, MA, 01003*
[4] *University of Pennsylvania, Dept. of Physics and Astronomy, Philadelphia, PA 19104*

Abstract. Lyα forest lines in QSO spectra have typical widths of $20-50$ km s^{-1}. Low column density absorbers in cosmological simulations are large, diffuse structures, and the Hubble flow across the spatially extended absorber is usually the dominant contribution to the width of its associated absorption line. Thermal broadening is unimportant over most of the spectrum, and peculiar velocities tend to make absorption features narrower rather than broader. As a consequence of Hubble flow broadening, there is a close relation between local Lyα optical depth and local neutral hydrogen density, which is well approximated by the Gunn-Peterson formula. The physics that governs the unshocked intergalactic medium leads to a tight correlation between the neutral hydrogen density and the underlying gas and dark matter overdensity. For many purposes, it is simpler to regard a Lyα forest spectrum as a continuous, non-linear map of the density field rather than a collection of discrete lines. This continuous field view of the Lyα forest can be applied to measurement of the baryon density parameter, testing of cosmological models, and robust determination of the shape and amplitude of the primordial mass power spectrum.

In the last few years, the study of the Lyα forest has undergone several observational revolutions: the extension to low redshift via HST, the probe of internal structure from spectra along neighboring lines of sight, the extraordinary detail provided by Keck HIRES data, and the clear detections of metals associated with low column density HI absorbers. The field has also undergone a theoretical revolution, driven by hydrodynamic cosmological simulations. These allow one to predict properties of the Lyα forest from *a priori* theoretical models motivated by independent considerations of large scale structure, the cosmic microwave background, and galaxy formation. Since the pioneering numerical study of Cen et al. [3], there have been more than 30 papers using cosmological simulations to investigate QSO absorption phenomena, by several independent groups. The resulting picture of the Lyα forest

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has features in common with some earlier models, especially the fluctuating intergalactic medium (IGM) scenario of Bi [2].

One distinctive feature of this cosmological picture of the Lyα forest is the low density of the absorbing structures. Typical marginally saturated lines ($N_{\rm HI} \sim 10^{14}$ cm^{-2}) arise in gas whose density is a few times the cosmic mean or less. Weak lines ($N_{\rm HI} \lesssim 10^{13}$ cm^{-2}) often occur at local maxima that lie below the global mean density. This low density has a number of important consequences. Most absorption arises in structures that are still expanding with residual Hubble flow. These absorbing systems are usually far from dynamical, hydrostatic, or thermal equilibrium. The low density implies a low recombination rate and thus a low neutral fraction (typically $\sim 10^{-6} - 10^{-4}$), so the neutral hydrogen revealed by the observed Lyα opacity is only the tip of a much larger iceberg.

The low density of the absorbing gas also means that absorbers must be physically large in order to produce the observed column densities. The large size implies that the Hubble flow across an absorber can be substantial. Indeed, for a typical low column density line in the simulations, the primary contribution to the line width (b-parameter) comes from Hubble flow. This situation contrasts with that in traditional conceptions of the forest, where lines are assumed to be broadened by thermal motions of the gas or by "turbulent" motions of cloudlets. Gravitationally induced peculiar velocities do distort the lines in cosmological simulations, but these *coherent* flows are not at all like Gaussian turbulence, where there is a large *dispersion* in the velocities at a given spatial position. Furthermore, because most lines with $N_{\rm HI} \gtrsim 10^{14}$ cm^{-2} arise in moderately overdense regions that are expanding slower than the Hubble rate, peculiar velocities on average have the effect of *narrowing* Lyα forest lines, not broadening them.

Figure 1 illustrates these points using spectra extracted along twelve random lines of sight through a hydrodynamic simulation of the "standard" CDM model (SCDM, with $\Omega = 1$, $h = 0.5$, $\sigma_8 = 0.7$) at $z = 3$ (see [9] and [4] for details). Solid lines show the full Lyα absorption spectra. Dotted lines show the spectra with no thermal broadening — they are computed by artificially setting the gas temperature to zero (without changing the neutral fraction). There are a handful of sharp features in the non-thermally-broadened spectra that are smoothed away in the full spectra. However, in most regions the dotted and solid lines are barely distinguishable, demonstrating that thermal broadening usually does not contribute significantly to the width of the absorption features. The dashed lines in Figure 1 show spectra with thermal broadening but no peculiar motions — they are extracted along the same lines of sight after setting the peculiar velocities of all gas particles to zero. Comparing the solid lines to the dashed lines shows that peculiar velocities do shift the positions and distort the shapes of individual absorption features, but they do not make them systematically broader. Indeed, as expected from the physical argument above, the lines in the full spectra tend to be somewhat narrower than the lines in the spectra with no peculiar velocities.

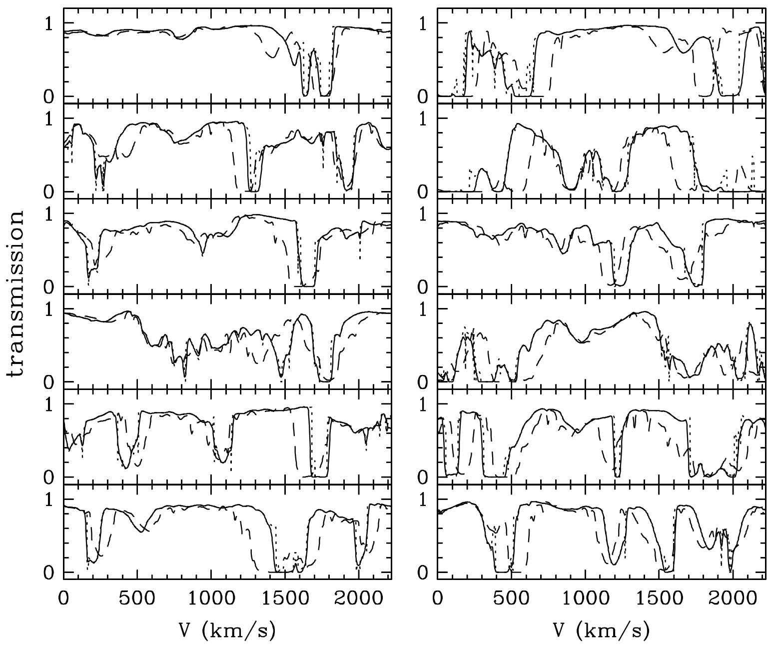

Figure 1: Solid lines show spectra along twelve randomly chosen lines of sight through a simulation of the standard CDM model, at $z = 3$. Dotted and dashed lines show spectra along the same lines of sight with no thermal broadening and no peculiar velocities, respectively.

Studies of QSO pairs [1, 6, 7] provide observational evidence for Hubble flow broadening of Lyα forest lines independently of cosmological simulations. The inferred transverse coherence scale of the absorbers, $l_t \sim 150h^{-1}$ kpc at $z \sim 2$, corresponds (for $\Omega = 1$) to a line-of-sight extent $H(z)l_t \approx 80$ km s^{-1}, considerably larger than the ~ 25 km s^{-1} b-parameter of a typical forest line [10]. Nonspherical absorbers would be preferentially intercepted "face on," but unless the absorbing structures are *highly* flattened the observed transverse scale implies that Hubble flow across them must make a major contribution to the line width. The transverse coherence could in principle be a signature of clustering of small clouds rather than a physical scale of large absorbers, but the nearly perfect coincidence of lines towards small-separation gravitational lens pairs [14, 15] argues against the clustering interpretation, and the detailed match of absorption features shown by Rauch in these proceedings seems to rule it out definitively.

Many papers have remarked on the low density of the absorbing gas in cosmological simulations (e.g., [3, 18, 9, 12, 19]). The issue of Hubble flow broadening has received less attention, but its implications are perhaps even more profound. For a start, it means that the profile of a Lyα forest line shows a line-of-sight density profile through the absorbing structure, albeit one that is non-linear and distorted by peculiar motions. This is not the case in the thermal broadening picture, where the absorber itself is compact and the wings of the line arise from high velocity atoms. In the cosmological picture, line wings show the absorbing structure itself fading into the background, like mountains into foothills.

Another consequence of Hubble flow broadening is that the Gunn-Peterson [8] formula,

$$\tau_{\rm GP} = \frac{\pi e^2}{m_e c}\, f_\alpha \lambda_\alpha H^{-1}(z) n_{\rm HI}, \tag{1}$$

provides a good approximation to the relation between local Lyα optical depth and the local space density of neutral hydrogen. In a thermally broadened, compact cloud model, by contrast, the optical depth is lower than $\tau_{\rm GP}$ at the line center (the redshift space location of the dense cloud) and higher than $\tau_{\rm GP}$ in the line wings (where there is no gas at the corresponding redshift space position). Cosmological simulations imply that the Lyα forest can be viewed as a fluctuating Gunn-Peterson effect, produced by an inhomogeneous, diffuse intergalactic medium.

What turns the fluctuating Gunn-Peterson idea from a novelty into a powerful conceptual tool is the simplicity of the physics that governs the ionization state of the low density gas. This gas is in photoionization equilibrium, so the neutral hydrogen density is $n_{\rm HI} \propto \rho^2 T^{-0.7}/\Gamma$, where Γ is the photoionization rate and the $T^{-0.7}$ factor accounts for the temperature dependence of the hydrogen recombination coefficient near $T \sim 10^4$ K. The interplay between photoionization heating and adiabatic cooling leads to a tight relation between temperature and density, which can be well approximated by a power law, $T = T_0(\rho/\overline{\rho})^\gamma$ [4, 11]. The values of T_0 and γ depend on the UV background spectrum and reionization history and can be computed semi-analytically [11]; typically $T_0 \sim 6000$ K and $\gamma \sim 0.3 - 0.6$. With this physical reasoning, equation (1) can be converted to a formula we can describe as the *fluctuating Gunn-Peterson approximation*,

$$\begin{aligned}\tau(\lambda_{\rm obs}) = \quad & 0.172 \left(\frac{\rho}{\overline{\rho}}\right)^\beta \left(1 + \frac{dV_{\rm los}}{H(z)dx}\right)^{-1} \left(\frac{1+z}{4}\right)^6 \left(\frac{H(z)/H_0}{5.51}\right)^{-1} h^{-1} \times \\ & \left(\frac{\Omega_b h^2}{0.0125}\right)^2 \left(\frac{T_0}{10^4\ {\rm K}}\right)^{-0.7} \left(\frac{\Gamma}{10^{-12}\ {\rm s}^{-1}}\right)^{-1}\ ,\end{aligned} \tag{2}$$

where $\beta \equiv 2 - 0.7\gamma$, $\rho/\overline{\rho}$ is the overdensity at the position where the redshift (cosmological plus peculiar velocity) is $\lambda_{\rm obs}/\lambda_\alpha - 1$, and $dV_{\rm los}/dx$ is the derivative of the line-of-sight peculiar velocity at the same position. The peculiar velocity term accounts for the mapping from real space to redshift space. In principle, $\rho/\overline{\rho}$ here refers to the *gas* overdensity, but because the temperature is low, pressure gradients are small compared to gravitational forces, and the gas traces the dark matter quite well.

Equation (2) is valid if all gas lies on the temperature-density relation and thermal broadening and collisional ionization can be ignored. The approximation breaks down when $\rho/\overline{\rho} \gtrsim 10$, but these regions occupy a small fraction of the spectrum. They are responsible for high column density lines, and the general description presented above begins to break down for $N_{\rm HI} \gtrsim 10^{15} - 10^{16}$ cm^{-2}. This description might also become less accurate at low redshifts; we have not examined the Lyα forest at $z < 2$ with our simulations. We should also note that *some* low column density lines at high z arise in shock heated gas and are thermally broadened.

A second useful approximation arises from ignoring peculiar velocities, setting $dV_{\rm los}/dx = 0$ in equation (2), so that there is a one-to-one relation between optical depth and overdensity. Figure 6 of [4] shows that the $\tau - \rho$ relation remains tight in simulated spectra even when peculiar velocities, thermal broadening, shock heating, and collisional ionization are all taken into account. The distribution of Lyα optical depths $P(\tau)$ is directly observable from high resolution QSO spectra [13], and one can use this second approximation to write the mean density of the "warm" IGM that produces the Lyα forest in terms of an integral over this distribution, $\overline{\rho}_{\rm WIGM} = \int_0^\infty \rho(\tau)P(\tau)d\tau$. After some manipulation, one obtains the density parameter of this warm IGM component [16, 17],

$$\Omega_{\rm WIGM} = 0.021 h^{-3/2} \left(\frac{\left[\int_0^\infty \tau^{1/\beta} P(\tau) d\tau\right]^{\beta/2}}{0.70} \right) \left(\frac{4}{1+z}\right)^3 \times \left(\frac{H(z)/H_0}{5.51}\right)^{1/2} \left(\frac{T_0}{10^4\ {\rm K}}\right)^{0.35} \left(\frac{\Gamma}{10^{-12}\ {\rm s}^{-1}}\right)^{1/2} . \quad (3)$$

For the fiducial value of the optical depth integral, we have used a value inferred from the observations of [13] at $z = 3$. The implied $\Omega_{\rm WIGM}$ is a substantial fraction of the baryon density parameter Ω_b allowed by big bang nucleosynthesis, indicating that most of the baryons in the universe at $z \sim 3$ resided in the Lyα forest, as the simulations predict.

The relation between the underlying mass distribution and the number density of Lyα forest lines in a spectrum may be physically complex, and it is sensitive to the details of the observational procedures and the method used deblend absorption features. However, the fluctuating Gunn-Peterson approximation implies that the relation between mass density and observed flux is direct and simple. If one wants to use the Lyα forest to test theories of structure formation, it is best to abandon lines altogether and treat the full observed spectrum as a continuous field. Statistical properties of this "flux field" are directly related to statistical properties of the underlying density and velocity fields, which are basic predictions of cosmological models. We are currently studying a variety of statistical measures similar to those used in large scale structure analyses, applying them to simulations in order to assess their sensitivity to different properties of the initial fluctuations and to values of cosmological parameters. We have also developed and tested a method to recover the shape and amplitude of the primordial mass power spectrum $P(k)$ from Lyα forest data [5], again motivated by the "continuous field" point of view. The 3-d flux power spectrum has the same shape as the mass power spectrum on large scales, and the normalization can be determined by evolving numerical simulations with this initial $P(k)$ shape until they reproduce the observed power spectrum of the QSO flux. Imposing the observed mean Lyα opacity as a constraint makes the derived $P(k)$ normalization insensitive to the choice of cosmological parameters, ionizing background spectrum, or reionization history. This approach thus neatly circumvents the uncertain physics of galaxy formation and "biasing," which complicates the interpretation of power spectra measured from galaxy redshift surveys. Application to existing samples of QSO spectra should soon yield the power spectrum of mass fluctuations in the high redshift universe.

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