THE LYMAN-ALPHA FOREST: A COSMIC GOLD MINE

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ABSTRACT. In recent years, a remarkably simple physical picture of the
Lyman-alpha forest has emerged, which allows detailed predictions to be made
and turns the forest into a powerful probe of cosmology. We point out ways in
which such a picture can be tested observationally, and explore three areas in
which the Lyman-alpha forest can yield valuable constraints: the reionization
history, the primordial mass power spectrum and the cosmological constant
or its variants. The possibility of combining with other high redshift observa-
tions, such as the Lyman-break galaxy surveys, to provide consistency checks
and complementary information is also discussed.

1 Introduction

The Ly forest was predicted and observed in the 60s (Gunn &
Peterson 1965, Bahcall & Salpeter 1965, Lyndes & Stockton 1966, Bur-
bidge et al. 1966, Kinman 1966; see Rauch 1998 for further ref). Since then, there have been many attempts to place the study of the
forest within the framework of cosmological structure formation theo-
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numerical simulations lent support to some of these ideas, while clar-
ifying the nature of the forest and allowing detailed predictions to be made (e.g. Cen et al. 1994, Hernquist et al. 1995, Zhang et al. 1995,
Pettigrew et al. 1995, Miralda-Escude et al. 1996, Bond & Wadsley 1997,
Theuns et al. 1998). We explain in this contribution the physical picture
of the forest that has emerged from these and other semi-analytical work
and discuss observational tests of this picture, and point out three examples of how such a picture allows us to make valuable cosmological
constraints from the forest.

2 Simplicity of the Forest

Numerical
simulations indicate that the low
column n-density \( N_{H_\perp} \approx 10^{14} \text{cm}^{-2} \)
Ly forest (for redshift \( z \geq 2 \)), which occupies a large fraction of any
given quasar absorption spectrum,
3.1 Reionization History

Here we explore some effects of the reionization history on a particular statistic called the b-distribution, which has been measured by several groups (e.g., Hui et al. 1995, Lu et al. 1996, Kinkan & Tytler 1997). The b-parameter refers to the width of a Voigt-pro - le t of an absorption line. The number of lines as a function of width is then the b-distribution. The picture outlined in Fig. 1 provides a simple interpretation of the measured widths. A model to eq. (2), a peak in velocity-space which is narrower than the thermal broadening with b₁ will appear as a peak of width the shape of a Voigt-pro le and a width of b₁. Hence, the measured b-parameter provides a direct indication of the temperature of the gas. On the other hand, structure from a-theory predicts and allows large-scale fluctuations where a peak of much wider than the local b₁, which means according to eq. (2), the corresponding peak is no longer given by a Voigt-pro le shape and its width reects more the scale of the fluctuation rather than the tem perature of the gas i.e. the measured b can no longer be equated with the thermal broadening with.

In more quantitative terms, we can always perform the following expansion around a given absorption peak:

\[ u = \exp\left[ \ln(u) + \frac{1}{2} \ln^2(u) \right] \]

where \( u_0 \) is the velocity coordinate of the line center, and the prime denotes differentiation with respect to u and the second derivative is evaluated at \( u_0 \). The 1st derivative vanishes because \( u_0 \) is a local extremum. This expansion gives none other than the Voigt-pro le itself: \( \exp\left[ (u - u_0)\right] \). Hence, the tted b-parameter would be \( b = \frac{1}{2} \ln \frac{u_0}{u} \). Assuming most tted absorption lines do arise from peaks in , and assuming is Gaussian random (as in the case of linear fluctuations, or in the lognormal model), it can be shown that the normalized distribution of lines is given by Hui
at the parameter term measures the broad distribution through the rare events which are unusually suppressed (hence the long tail), while low b-peaks are sharp fluctuations which are statistically rare.

This model also tells us what determines the b-distribution, through the parameter \( b \): I. the (dimensionless) average amplitude of the fluctuations (how nonlinear the ekd is; see below), and II. the three smoothing scales in the problem: the observation resolution, the average thermal broadening scale and the baryon-smoothing-scale due to the gas pressure; for high-quality Keck spectra, the rest is probably negligible, while the latter two are comparable.

How do the thermal broadening scale and the baryon-smoothing-scale change with reionization history? For a fixed redshift of observation (say \( z = 3 \)), as one raises the redshift of reionization, the temperature at \( z = 3 \) becomes lower (Hui & Gnedin 1997) and the thermal broadening scale becomes smaller. The effect on the baryon-smoothing-scale is more subtle. It is true that the Jeans scale, like the thermal broadening scale, is proportional to \( T \), and so lowering the temperature lowers both. However, as shown by Gnedin & Hui (1998), the true baryon-smoothing-scale is in fact not given by the Jeans scale, but generally given by something smaller. In fact, right before reionization occurs, the baryon-smoothing-scale is very small, and as a result, the baryon-smoothing-scale does not suddenly jump up to the conventional Jeans scale, but only slowly catches up with it. This means that raising the redshift of reionization could have the opposite effect of allowing a larger baryon-smoothing-scale by allowing more time for it to catch up with the Jeans scale. Therefore, exactly how raising the redshift of reionization affects the b-distribution requires a detailed calculation.

This is a subject of much current interest, particularly because of the work of Bryan et al. (1998) (see also Haehnelt & Steinmetz 1998, Theuns et al. 1998) who, after carefully investigating the effect of numerical resolution and box-size on the b-distribution, found that the canonical \( s = 0.1 \) SCDM model predicts a b-distribution that has too many narrow lines than is observed, if the universe reionized by \( z \approx 6 \). The interesting questions are: I. changing the reionization amplitude will likely shift the b-distribution, but which way will it go? - the arguments leading to eq. 6 indicate that lowering the amplitude would move the b’s up (because lowering the amplitude means more suppression of sharp fluctuations or narrow lines), but as pointed out by Hui & Rutledge (1998), nonlinear corrections could reverse this trend; II. reionization history will no doubt affect the shape of the b-distribution, but as pointed out above, which direction it will go is not obvious and requires a detailed calculation; III. as noted by Hui & Gnedin (1997), the mean temperature of the intergalactic medium increases with \( b \) (see also Bryan et al. 1998) and decreases with \( m \); it would be interesting to see whether changing these would x the discrepancy of Bryan et al.

It is clear from the above discussion that the influence on reionization history from the b-distribution will depend on assumptions made about the cosmological density parameters and the power spectrum normalization. To isolate the effect of reionization history from the effect of power spectrum normalization, one possibility is to consider the lowest b’s, which according to our picture, should correspond to the minimum size imposed by either the thermal broadening scale, or the baryon-smoothing scale. However, one should keep in mind the

2 \( T \) is quite independent of \( J_{H_{1}} \) as long as \( H \) is at least partially ionized, but does depend somewhat on \( J_{H_{1}} \).
possible complication that not all tested absorption lines arise from peaks in , e.g., some narrow lines might be introduced to the wings of absorption peaks which do not necessarily have Voigt-profile shapes, in which case the physical meaning of the widths of these lines is unclear. One should check for this possibility using simulations, even develop other characterizations of the line width which are less prone to systematics of this sort.

3.2 The Primordial Mass Power Spectrum

This is an area pioneered by Croft et al. (1998), who showed that the linear mass power spectrum can be reliably recovered from the power spectrum of the transmission. The idea works as follows. The transmission power spectrum $P_\ell$ along the line of sight and the three-dimensional mass power spectrum $P$ are related to each other on large scales by (Hui 1998):

$$Z_1 \frac{P_\ell}{P} = \frac{B W(k, z)}{B k} k \Delta(k) dk \Gamma(k)$$

where $P_\ell$ is the fourier transform of the two-point correlation $h_\ell(B)$, $W(k, z)$ is the window function characteristic of the corresponding three-dimensional mass vector along the line of sight, and $k$ is the magnitude of the corresponding three-dimensional mass vector. The kernel $W(k_0, z)$ describes the redshift-distortion of the power spectrum. $B$ is a constant which is determined by the nonlinear transformation from density to the transmission $\exp(-\Delta(k))$ (eq. 6). Fortunately, the only free parameter that enters into the determined fraction of the constant $B$ is the constant $A$ in eq. (4) which can be fixed by matching e.g., the observed mass transmission (Croft et al. 1998). It is important to realize that we have made use of the facts that have a small range (eq. (2)) and that the uncertain them broadening and baryon smoothing scales only affect the transmission correlation on small scales, and that the dark matter and baryon distributions trace each other on large scales.

It is expected eq. (4) holds on large scales with $P$ being the linear power spectrum. Hence, once the distortion kernel is fixed (which is predicted by gravitational instability, with dependence on the cosmological density and redshift parameters $\nu_1$), the primordial mass power spectrum can be recovered from $P_\ell(k)$ by inverting an essentially triangular matrix proportional to the distortion kernel (Hui 1998).

There are two main advantages of this way of ensuring the linear mass power spectrum. First, unlike in the case of galaxies, the biasing relation between density and the observable (the transmission) is known exactly here (aside from the parameter $A$ which can be fixed using independent observations). Second, this provides a direct probe of the linear mass power spectrum on small scales ($k < 0.025$ $k$- $3 H$ $Mpc^{-1}$, for $z = 3$; see Croft et al. 1998), which are out of the reach of galaxy surveys at low redshifts (unless one corrects for the nonlinear evolution). This is simply because the nonlinear scale becomes smaller at higher redshifts.

Exciting (and beautiful!) results of the application of the above techniques to the observed forest were reported recently by Croft et al. (1998b), W. Weinberg et al. (1998) (see also contribution to this volume by W. Weinberg). Here, let us list a few issues that deserve some thought and perhaps further investigation. I. The distortion kernel $W$ above can be predicted using linear theory, but it is quite possible that the highly nonlinear transformation from the density to the transmission will alter its behavior, even at very large scales (M. Donald & M. Malhi-Escudé 1998, Hui 1998). This should be carefully checked using simulations. II. There is an upper limit to the scale above which we cannot reliably recover the mass power spectrum. It is set by the continuum, which is known to have long range fluctuations, and which can only be estimated up to a limited accuracy. This limit is around $k = 0.025$ $k$- $3 H$ $Mpc^{-1}$, but should be checked carefully using high resolution observations. III. The whole inversion procedure discussed above relies on the fact that eq. (4) holds for most of any quasar spectrum, aside from regions of strong absorption such as
3.3 The Cosmological Energy Contents

Here, we discuss a version of a test proposed by A. Lock & F. Paczynski (1979; AP hereafter), which is particularly sensitive to the presence of the cosmological constant \( \Lambda \), or more generally, a component of the cosmological energy content which has negative pressure, let us call it \( Q \), with an equation of state \( p = w \) (\( w < 0 \)). The ideas presented here have been considered by several groups recently (Coff 1998, Seljak 1998, McDonald & M. Zaldarriaga 1998, Hui, Stebbins & Burles 1998).

AP observed that an object placed at a cosmological distance would have a definite relationship between its angular and redshift extents, which is cosmology-dependent. Consider an object with a mean redshift \( z \), and angular size \( \theta \), its transverse extent in velocity units is

\[
u_{\text{r}}(\theta) = \frac{H}{1+z} D_A(z)\]  \(\text{(5)}\)

Here \( H \) is the Hubble paramater at redshift \( z \), and \( D_A(z) \) is the angular diameter distance (Weinberg 1972). For spherical objects the radial and transverse extents are equal, but more generally if the object is squashed radially by a factor \( s \), the radial extent is

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For instance, while one expects that resolution can be sacrificed as long as one is interested in large scale fluctuations, resolution does affect the seeing of the amplitude \( A \) using the observed mean transmision \( C \) (Coff, priv. com. m.). Analytical methods to \( x^{2/3} \) would be very useful. The tem penum-density relation mentioned in \( A \) is expected to have a scatter. It would be good to have an idea by how much it could modify the transmission power spectrum, or in other words, the "biasing" relation between density and transmission.

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The Cosmic Energy Cont. A

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where \( J_0 \) is the spherical Bessel function. This prediction is cosmology.
dependent mainly through the parameter $u$, and also through the distortion kernel $W_{k}$. The latter generally depends on an effective bias parameter (Hui 1998), aside from the cosmological density parameters of interests, which can fortunately be determined from simulations because the exact biasing relation between density and the observable (the transmission) is known (eq. [1]), unlike in the case of galaxies (where the AP test has been contemplated by other authors). A comparison of the predicted with the observed cross-spectra, for a given observed auto-spectrum, provides a version of the AP test: assuming the wrong cosmology will result in a wrong prediction for the cross-spectrum. Note that in this test, there is no need to x the constant $B$ because it enters into the auto- and cross-spectra in the same way.

According to Hui et al. (1998), to reach a level discrimination between e.g. the $n = 0.2 - 0.7$ universe and the $n = 0.3 - 0.7$ universe, only 25 pairs of quasar spectra at angular separations $\theta < 2^\circ$ would be required. These are roughly 10 such pairs of quasars with existing spectra at the above angular separations, or slightly larger, and at $z \leq 1$ (see e.g. Crotts & Fang 1998 & ref. therein). Upcoming surveys such as the AAT 2dF and SDSS are expected to increase this number by at least an order of magnitude, and to higher redshifts.

4 Tests and More

The cosmological utility of the (low column density) forest relies very much on the simple relation between the optical depth or transmission and the density-velocity fields, which arises from the fact that I. the distribution of the latter is determined by gravitational instability alone on large scales, and by baryon-smoothing on small scales (e.g. explosions do not play an important dynamical role); II. the ionizing background $J$ does not have significant spatial fluctuations on scales of interest (see [2]). Here, we loosely refer to this whole set of assumptions as the smooth-quantum-paradigm. The ability of mass current simulation-inspired work on the forest, which makes use of the above assumptions, to explain the observed $b$ and column-density distributions should be considered as a vindication of the paradigm. After all, this body of work is based on structure formation models constructed to match observations other than those of the forest. Moreover, there are theoretical reasons to believe that $J$ fluctuations should be small on all the scales we are interested in (e.g. Crotts et al. 1998b). Nonetheless, it is important that we find alternative ways to test our assumptions observationally, as we continue to look for new applications of the forest in cosmology.

Here, we discuss three possible tests that involve only the forest, and one cross-test with another high redshift observation.

I. Use double (or multiple) lines of sight. There are in fact two different tests here. First, for quasar pairs that are very close together e.g. lensed pairs, one can check whether the cross-correlation between the forest in the two lines of sight is as strong as the one would expect based on the smooth-quantum paradigm. More specifically, for lensed quasar pairs which are typically of the order of arc-second separation, the distance between the two lines of sight is sub-kpc, which is much smaller than the baryon-smoothing scale expected for a gas of $T \leq 10K$. This means one expects 10% correlation between these two lines of sight through the forest. Exactly such a behavior has been observed by Rauch (1997). This shows that the forest has an important role in the ionizing background, nor is there complicated motion in the forest due to explosions, at least on these small scales. For quasar-spectra at larger separations, on the other hand, assuming a set of $J's$, one can turn the procedure in [2] around, and test for the redshift-anisotropy due to peculiar motion. This is a robust prediction of gravitational instability. Any other source of fluctuations, such as that due to a fluctuating background, will act as additional sources of "biasing", and change the prediction for the redshift-anisotropy.

II. Use higher order statistics. It is well known that gravitational instability gives robust predictions for
higher order statistics such as the skewness \( h^{-3} \) (Geebikus 1980), where \( h \) is the overdensity in \( m \) mass. Just as in the case of galaxies, where \( m \) is measured the skewness of the galaxy distribution \( h^{-3} \)

where \( g \) is the galaxy overdensity, provides information on the biasing relation between \( m \) mass and galaxy distributions. From this relation, we should be able to see their mass.

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For instance, once the \( m \) mass power spectrum is inferred from the forest, a comparison with the clustering of the Lym \( \text{an-alpha} \) objects would immediately yield a measure of the bias of the Lym \( \text{an-alpha} \) galaxies. On the other hand, the bias of the Lym \( \text{an-alpha} \) objects can be obtained from observations of the Lym \( \text{an-alpha} \) objects themselves. Either by a direct measurement of their \( m \) masses (using high resolution infrared observations, which should be feasible in the near future), or by measuring the skewness of the galaxy distribution.

Note that to deduce from either quantity the bias (as defined by the square root of the ratio of the galaxy power spectrum to \( m \) mass power spectrum), one needs a model for how these galaxies form i.e. how they are formed in relation to dark matter halos (M o et al. 1998).

With the above information in hand, we have two independent measurements of the \( m \) mass power spectrum at \( z \), one from the Ly \( \beta \) forest, the other from the Lym \( \text{an-alpha} \) objects. Making use of the deduced bias parameter, they probe the clustering at different scales, and so one can use them to constrain the shape of the power spectrum; or, if one assumes a particular cosmological model with a definite power spectrum shape, one can test for consistency. Moreover, the latter approach also allows a two independent measurement of \( m \) (with minor dependence on the other parameters), by comparing with the cluster- or aligned \( m \) mass-power spectrum today (see e.g. G iavalisco et al. 1998, A delberger et al. 1998, W einberg 1998). Investigations along these lines are being pursued.

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