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R Croft

D Weinberg

N Katz
University of Massachusetts - Amherst

L Hernquist

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Cosmology from the structure of the Lyα forest

Rupert A.C. Croft, David H. Weinberg
Dept. of Astronomy, Ohio State University, Columbus, OH 43202, USA.

Neal Katz
Dept. of Physics and Astronomy, University of Massachusetts, Amherst MA 01003, USA.

Lars Hernquist
Lick Observatory, University of California, Santa Cruz, CA 95064, USA.

A convincing physical picture for the Lyα forest has emerged from simulations and related semi-analytic studies of structure formation models. Observations can be be used in the context of this picture to study cosmology using the structure of the forest. With the availability of well motivated predictions, not only has it become possible to test models directly, but the physical processes involved appear to be simple enough that we can attempt to reconstruct aspects of the underlying cosmology from observations. We briefly summarise the method of Croft et al. (1997) [1] for recovering the primordial mass power spectrum from Lyα forest data, emphasising the physical reasons that the derived P(k) is independent of unknown "bias factors". We present an illustrative application of the method to four quasar "spectra" reconstructed from published line lists.

1 Introduction

Observations of structure in the Universe contain cosmological information. This realisation has been the driving force behind much work done in mapping the distribution of galaxies, statistical analyses of which have been used in attempts to estimate Ω, measure the power spectrum of matter fluctuations, constrain the nature of dark matter, and so on. This has been done in the context of the theory of structure formation by gravitational amplification of small initial perturbations, but before the existence of any detailed predictive "theory of galaxy formation". This usually only allows for an interpretation of observations which includes unknown free parameters, most often involving the relationship between galaxy and mass fluctuations. Recent work[2,3,4,5,6] has shown that the gravitational instability theory first invoked to explain the distribution of galaxies also naturally makes predictions for the existence and nature of QSO absorption phenomena. The physical processes responsible for most QSO absorption at high redshift (here we will concentrate on the Lyα forest caused by neutral hydrogen) appear to be simple enough that we can understand and simulate them reliably. Therefore, a "theory of Lyα forest formation" does exist, which can be taken advantage of to study cosmology in a way which can only be done with the galaxy distribution once there is a "theory of galaxy formation".

This contribution to the proceedings concerns one optimistic way of viewing the situation, namely that if the picture we have for the formation of the Lyα forest is broadly correct, then we can ask what this entails for our cosmology. The primordial power spectrum of matter fluctuations, P(k) is of particular interest. We will briefly summarise a method (details are in [1]) for estimating this quantity and give some illustrative results.

2 Reconstruction of P(k) from the Lyα forest

To reconstruct P(k), a statistic based on the mass distribution, we first need to understand how the Lyα forest of absorption is related to the mass distribution in our chosen theoretical picture, the gravitational instability scenario for structure formation. Hydrodynamic simulations and semi-analytic work have revealed that the high-z Lyα forest arises in the large fraction of space where the density of matter is within a factor of 10 of the cosmic mean. In these regions, pressure effects are relatively unimportant, so that the gas tends to trace structure in the dark matter. The local density of matter also governs the temperature of the gas, which follows a power law temperature-density relation[7], $T = T_0 \rho^{0.6}$, where ρ is the density in units of the cosmic mean. This relation arises because of the interplay between photoionization heating by the UV background and adiabiatic cooling by the expansion of the Universe. If we ignore other effects for the moment, such as thermal broadening, peculiar motions and collisional ionisation, we can infer that the optical depth for absorption (τ) and the local density obey the following approximate relation:

$$\tau \propto n_{HI} = A\ \rho^{\beta}, \tag{1}$$
$$A = 0.946 \left(\frac{1+z}{4}\right)^6 \left(\frac{\Omega_b h^2}{0.0125}\right)^2 \left(\frac{T_0}{10^4\ \mathrm{K}}\right)^{-0.7} \left(\frac{\Gamma}{10^{-12}\ \mathrm{s}^{-1}}\right)^{-1} \left(\frac{H(z)}{100\ \ \mathrm{km\ s}^{-1}\ \mathrm{Mpc}^{-1}}\right)^{-1},$$

where n_{HI} is the neutral hydrogen density. β is ~ 1.6 and the parameter A is a function of the baryon density (Ω_b), the photoionization rate (Γ),T_0, z and H_0. The flux observed at a point in the QSO spectrum, F, is given by $e^{-\tau}$. This relation between flux and mass is analogous to the local biasing relations which have been postulated to exist between galaxies and mass. The difference here is that it is a prediction directly derived from theory, and that the parameter A can be inferred from observations, as will be explained below.

As the relation between flux and mass is local, we would expect the shape of the power spectrum of the flux to be the same above some scale as the shape of P(k) for the mass. In tests on simulations, we find that this is indeed the case for $\lambda > 1.5\ h^{-1}$Mpc. In our method we therefore recover the shape of P(k) for the mass from the power spectrum of the flux. There are two additional twists that we incorporate at this stage. The first involves the fact that by taking an FFT of a QSO spectrum we measure the power in 1 dimension. As we are interested in P(k) in 3-d , we must convert the quantity to 3-d, which involves as simple differentiation (see [1], equation 5). The second is that as we are interested in the initial, linear P(k) of the mass, we apply a monotonic transformation to the flux, to give it a Gaussian pdf, before measuring P(k). This step is motivated by the fact that under gravitational instability, the rank order of (smoothed) densities is seen to be approximately conserved[8], so that one way of recovering the initial density field is to monotonically map the final densities back to the initial pdf[8], here assumed to be Gaussian. As this is a local transformation, it does not alter the shape of P(k) for $\lambda > 1.5\ h^{-1}$Mpc, but it does have the effect of slightly reducing the noise level.

We now have the shape of the mass P(k), but not its amplitude. To find this normalisation, we use the fact that a higher amplitude of mass fluctuations will result in larger fluctuations in the flux. We can therefore run simulations set up using the mass P(k) shape we have derived but with different mass amplitudes, and pick the mass amplitude which yields the observed level of flux fluctuations in the simulated spectra we extract. The measure of flux fluctuations we use is the power spectrum of the flux. In carrying out this procedure, we must bear in mind that a number of other factors may also influence the amplitude of flux fluctuations. The first of these is obviously the parameter A in equation (1), as a larger value of A will give larger flux fluctuations for a given set of ρ (mass) fluctuations. Luckily, as mentioned above, the value of A can actually be fixed using a measurement made independently from the observations. This measurement is the mean flux level $\langle F \rangle$ in the observations, which, for a given set of mass fluctuations, will specify A uniquely. Being able to make this measurement is analogous to being able to measure the mass associated with each galaxy, which would then specify galaxy biasing exactly. Once we have fixed A, we have to pick the other parameters we need to run the normalizing simulations, such as the value of Ω, the mean temperature of the gas, and so on. Varying these parameters has little effect on the results, basically because the approximation of equation (1) is a good one on the scales where we are interested in measuring P(k).

For speed, our normalising simulations are run not with a full hydro code, but with a PM N-body code, assuming that gas and dark matter follow each

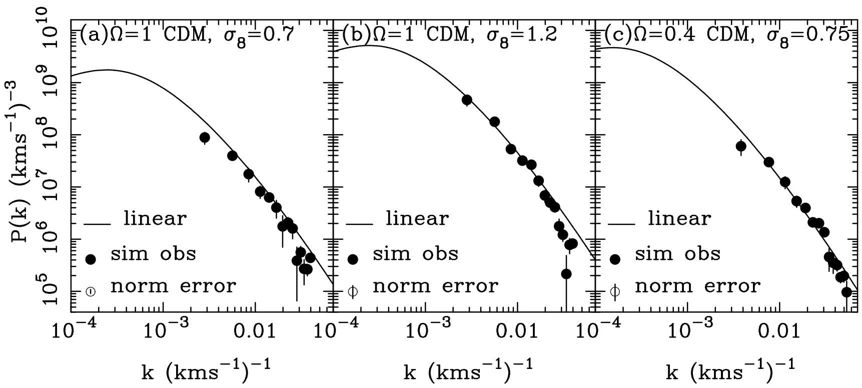

Figure 1: The mass power spectrum, P(k), recovered from simulated observations of the Lyα forest at $z = 3$ (see text). The simulations used were of three different CDM models, with parameters listed at the top of each panel. H_0 was 50 km s^{-1}Mpc^{-1} for (a) and (b) and 65 km s^{-1}Mpc^{-1} for (c). An estimate of the error in the overall normalisation of the recovered (solid) points is shown in the bottom left. The true linear P(k) for each model is shown as a solid line.

other closely. We have compared this approach to the full hydro case and find that it works very well for our purpose. We now demonstrate the application of our P(k) reconstruction method to observations, both simulated and real.

3 Illustrative results

We test the method by using full hydrodynamic simulations run with the TreeSPH code[4], which includes gas pressure, collisional ionisation, shock heating, star formation and other effects not explicitly included in the approximate description listed above. We use these simulations (of three different CDM models) to create QSO spectra, which we rebin into coarse (40 km s^{-1}) pixels and then add Possion photon noise (S/N=10) to, in order to simulate medium quality (not state of the art) observations. These simulated spectra (for $z = 3$) are then analysed with the P(k) reconstruction method, using enough lines of sight through the simulation box to be equivalent in length to 5 QSO spectra. The results are shown in Figure 1, together with a curve showing the correct linear theory P(k) for each model. These results are displayed in the relevant observational units, km s^{-1}, but in each case, the largest scale point corresponds to the largest mode in the simulation box, which has wavelength $\lambda = 11.11\ h^{-1}$Mpc. Figure 1 shows that we can recover P(k) reasonably well on scales from $\sim 1 - 10\ h^{-1}$Mpc.

In advance of an application to a large sample of observational data, we have obtained some illustrative results by applying the method to some pub-

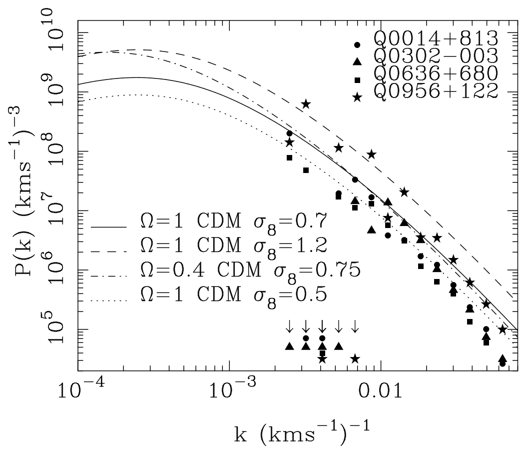

Figure 2: Symbols show the mass power spectra recovered from the Lyα forest in four QSO spectra reconstructed on the basis of published line lists (taken from [9]). The linear theory power spectra for different CDM models at the same mean redshift $z = 2.9$ are also shown.

lished data from [9] for 4 quasars, also of absorption at $z \sim 3$. The published data is in the form of lists of lines with Voigt profiles into which the spectra have been decomposed. We have reconstructed the spectra on the basis of these lists, as in our theoretical picture we need a continuous flux distribution which we relate to the continuous mass distribution. There may be unknown systematics involved in this reconstruction from line lists, so it should be borne in mind that the results which we show (in Figure 2) are for illustrative purposes only. We can see that the reconstructed P(k), whilst being consistent with low amplitude CDM models exhibits large scatter from quasar to quasar. In some cases, the differentiation required to convert 1-d power to 3-d power yields a negative P(k) because of noise; in such cases we plot a point at the base of the figure. There exist large samples of data, most at lower resolution, which we hope to use soon in a definitive reconstruction of P(k).

4 Discussion

So far we have assumed that the photoionising UV background is completely uniform, when in fact it is probably produced by discrete sources such as QSOs and Population III stars . This would cause fluctuations in the local value of the photoionisation rate which enters into equation (1) and so cause fluctuations in the flux on top of those associated with the value of ρ at that point. Other effects could also cause inhomogenous heating of the gas which could also affect the accuracy of our approximations. It would be surprising, however, if any of these effects were strong enough to change our P(k) measurement substantially. This is because on the scales we are estimating P(k), the fluctuations caused by the mass are of order unity, and any competing physical effect would have to be of similar strength and occur over most of the QSO spectrum to make a difference. A rough estimate (made in the optically thin limit) of the amplitude of fluctuations expected to be caused by QSO discreteness was made in [10]. It was calculated that on the largest scales we measure P(k) here , the fluctuations in the background would make a contribution to P(k) of about 2% of that expected to come from the mass. A higher density of sources should in principle cause smaller fluctuations. We can be reasonably confident that more detailed simulations will not change these preliminary conclusions.

Apart from the reconstruction of P(k), the theoretical picture for the origin of the Lyα forest used in this paper has already been used to constrain the baryon density[11,12] and directly test cosmological models[11]. Particularly with an extension to three dimensions by cross-correlating the spectra of nearby quasars, it seems as though there should be many other ways that the Lyα forest can be used to robustly constrain our cosmology.

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