THE LYMAN-ALPHA FOREST AS A PROBE OF COSMOLOGY

RUPERT A.C. CROFT[1]

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ABSTRACT

In cosmologies where structure formation is driven by gravitational instability, simple physical processes govern the relationship between the matter density field and an observable quantity, the absorbed flux in the Lyman-alpha forest region of QSO spectra. With this knowledge, we can reconstruct statistical properties of the mass distribution and so constrain cosmological theories. Lyman-alpha forest data can then be put to a number of uses. In this article we briefly review some of them. These include measurements of the power spectrum of mass fluctuations, the cosmological density parameter Ω_M, and the fraction of matter in the form of baryons, as well as constraints which can be placed on specific cosmological models.

Subject headings: Cosmology: observations, quasars: absorption lines, large scale structure of universe

1. INTRODUCTION

Traditionally, studies of the clustering of matter in the Universe have been one the the main ways used to infer the nature of matter and the values of global cosmological parameters. If they could be made, direct measurements of the power spectrum of mass fluctuations could distinguish between different cosmological models, and yield information on the transfer function, and initial fluctuations (e.g., from Inflation). The growth rate of clustering also depends on the cosmic density and cosmic geometry. In order to derive this information, however, one needs a reliable tracer of the mass distribution. Luminous objects such as galaxies, and quasars are related to the underlying mass field in unknown and presumably complicated ways. Our limited knowledge of this relationship has led away from attempts to measure matter clustering from objects such as galaxies, towards the use of gravitational lensing, cosmic velocity fields, galaxy cluster abundances and other techniques to probe the dark matter and cosmology.

Beginning around 1994, it was widely realized that the Lyα forest is a potential tracer of the matter density field for which we do have a good physical model and understanding, so that is might be possible to infer matter clustering from it and study cosmology. The Lyα forest is a complex of absorption features seen in quasar spectra which are due to neutral hydrogen in the intergalactic medium (see the review by Rauch 1998). The acceptance of our theoretical model for the Lyα forest was mainly motivated by a physical understanding derived from numerical hydrodynamic simulations (e.g., Cen et al. 1994, Zhang et al. 1995, Hernquist et al. 1996; although see also earlier analytic models by, e.g., Bi 1993). In these, at high redshifts (above $z \sim 2$), most of the baryonic matter in the Universe is in a continuous fluctuating medium. The physical state of this gas is very simple, being governed by the photoionization and photoheating of the ultra-violet background radiation, and the adiabiatic cooling which results from the expansion of the Universe (Hui & Gnedin 1997). Because of the low densities and pressures involved, on scales above a few hundred Kpc (the Jean's scale), the gas is a good tracer of the dark matter. The absorption caused by residual neutral hydrogen in the IGM can then be used to map out the dark matter, with the Gunn-Peterson (1965) formula for absorption by uniformly distributed neutral hydrogen being adapted for the case of a fluctuating density field. The relationship between Lyα optical depth, τ (the observable quanitity being flux, $F = e^{-\tau}$), and density ρ (in units of the mean) can then be written as (see e.g., Croft et al. 1999b)

$$\tau = A\rho^{\beta}, \tag{1}$$

$$A = 0.433 \left(\frac{1+z}{3.5}\right)^{6} \left(\frac{\Omega_b h^2}{0.02}\right)^{2} \left(\frac{T_0}{6000\,\mathrm{K}}\right)^{-0.7} \times \left(\frac{h}{0.65}\right)^{-1} \left(\frac{H(z)/H_0}{3.68}\right)^{-1} \left(\frac{\Gamma_{\rm HI}}{1.5\times 10^{-12}\,\mathrm{s}^{-1}}\right)^{-1},$$

with β in the range $1.6-1.8$. Here $\Gamma_{\rm HI}$ is the HI photoionization rate, and T_0 the temperature of the IGM at the mean density.

As a tracer of the matter field, the Lyα forest of absorption has a number of useful properties. It probes the Universe at high redshifts ($z \sim 2-6$), something which is interesting in its own right, but which also means that structure in the Universe was still close to linear in its development. The lines of sight towards quasars pass through random regions of the Universe, so that the Lyα forest is an unbiased tracer. It is a sensitive probe of most of the volume of space, even regions with densities well below the mean, where galaxies and other luminous objects would never form.

In this review, we briefly describe how the Lyα forest can be used to make measurements of various quantities of cosmological interest, including the baryon density (§2), the power spectrum (§3), the cosmological constant (§4), and others (§5). We summarize in §6.

2. THE BARYON DENSITY

As baryonic matter is actually responsible for the absorption seen in the spectra, the most obvious quantity to measure from the Lyα forest is Ω_b, the ratio of baryonic matter density to the critical density. Looking at Equation 1, we can see that there are other quantities which are degenerate with Ω_b in their effect on the measureable

[1]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138; rcroft@cfa.harvard.edu

quantity, the optical depth to absorption. If we make use of prior constraints on the temperature of the IGM, and the Hubble constant, one can add up the observed quasar sources of the UVBG to give a lower limit to the photoionization rate, Γ, which then enables one to infer a lower limit to Ω_b (see Weinberg et al. 1997). Interestingly, this lower limit is greater than half of the nucleosynthetic bound (Burles & Tytler 1997), implying that most of the baryonic content of the Universe at $z \sim 3$ lay in the diffuse photoionized gas which can be probed with the Lyα forest.

More accurate measures of Ω_b from the Lyα forest rely on better knowledge of the UVBG intensity (e.g. Rauch et al. 1997, Haehnelt et al. 2001, Hui et al. 2001). These analyses give results which are even closer to the BBN value. Problems to be overcome in determining a precise measure of Ω_b include the need for better knowledge of the QSO spectral continuum (the "zero-level" of the flux), which at present is fitted empirically using low-order polynomials. Also important is a better accounting of the sources of the UVBG radiation. This field is advancing rapidly, since it was discovered that high redshift galaxies are significant contributors (Steidel, Pettini and Adelberger 2001). While the determination of Ω_b from the Lyα forest may not have the precision of the BBN result, it is certain that, thanks to the Lyα forest, we have observed where the majority of the cosmic baryons are at $z = 3$, a situation which has not yet been resolved at $z = 0$.

3. THE MATTER POWER SPECTRUM

In order to achieve our goal of probing cosmology using measures of the clustering of matter, we can study Equation 1 again, a direct relation between a measurable quantity, the Lyα forest optical depth (or flux), and the mass density field at a point in space. Unfortunately, a direct inversion of Equation 1 is not practicable, for two reasons: the value of the constant A is not known a priori, and, more important, there are saturated ($F = 0$) regions in the spectra, which would give formally infinite densities.

The approach set out in Croft et al. (1998) aims to get round both of these problems. The power spectrum of the flux is calculated first, by directly Fourier transforming the quasar spectra. The relationship between this quantity and the linear matter power spectrum is then set by using numerical simulations for calibration. Mock spectra drawn from these simulations have their mean flux level set to match that seen in the observational data, which automatically fixes the constant A in Equation 1 to have the correct value. The calibration stage makes use of the fact that fluctuations in the flux are monotonically related to fluctuations in the underlying matter field (see Equation 1). The simulation output with the same flux power spectrum (flux fluctuations) as the data will have the same underlying mass fluctuation amplitude.

This procedure results in a measurement of the linear matter power spectrum at the redshift of the Lyα absorption. The length scales over which the measurement is reliable are limited on the low end to wavelengths of a few hundred h^{-1}kpc by thermal broadening, and on the upper end to $\sim 10 - 20$ h^{-1}Mpc by cosmic variance and continuum fitting uncertainty. Various refinements to the technique have been introduced to deal with redshift distortions and the effect of non-linearities on the shape of the power spectrum (see McDonald et al. 2000, Zaldarriaga, Hui & Tegmark 2000, Croft et al. 2001).

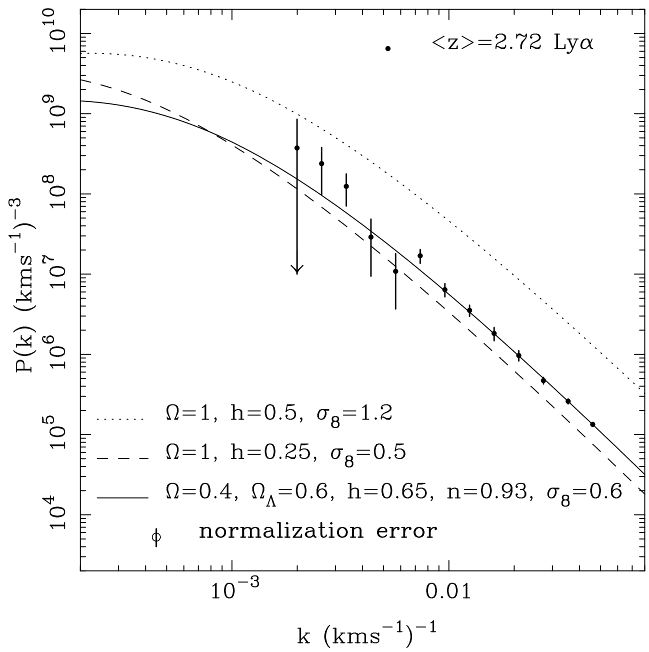

FIG. 1.— Comparison of the linear matter power spectrum inferred from a Lyα forest sample of 53 quasar spectra to the predictions of three inflationary CDM models (from Croft et al. 2001). Points with error bars show the inferred $P(k)$; at the 1σ level these points can be shifted coherently by the normalization error bar shown in the lower left. Dotted and dashed lines show, respectively, COBE-normalized and cluster normalized CDM models with $\Omega_m = 1$. The solid line shows a low-Ω_m model with a cosmological constant. While the models represented by the solid and dotted lines have quite different power spectrum shapes in comoving h^{-1}Mpc units, they have similar shapes here because of the different values of $H(z)/H_0$ for the two cosmologies.

In Figure 1 we show results for the linear power spectrum, $P(k)$ at $z = 2.72$ from Croft et al. 2001, together with power spectra from various cosmological models. The reader should note that the units of the measurement are km s^{-1}. On the scales probed, the Lyα forest result has the characteristic slope of ~ -2.5 expected of inflationary CDM models, and a similar amplitude. This is reassuring, as Lyα forest determinations constitute the first measurements of the linear matter power spectrum on these scales.

As well as discriminating between models directly, based on $P(k)$, we can also combine the Lyα results with other measurements in order to infer cosmological parameters. One example is a determination of the matter density Ω_m which can be made by combining the Lyα $P(k)$ with a constraint from the local number density of galaxy clusters. The latter fixes $\sigma_8 \Omega_m^{0.6}$, where σ_8 is the matter fluctuation amplitude (proportional to the square root of the power spectrum). The uncertainty due to σ_8 can be eliminated by using the value from the Lyα $P(k)$, which leaves a determination of Ω_m (Weinberg et al. 1999). The most recent application of this technique gives $\Omega_m = 0.5^{+0.13}_{-0.1}$ for flat models (Croft et al. 2001).

Combining Lyα forest measurements on small scales with microwave background anisotropy measurements on large scales is also a profitable way to use the information contained within both. Analyses which do this and draw constraints on the Hubble constant, primordial spectral index of fluctuations, Ω_b and other parameters include Novosyadlyj et al. (2000), Phillips et al. (2001), Wang et al. (2001). A similar combined analysis by Croft, Hu and Davé (1999) was targeted towards constraining the neutrino mass. The slope and amplitude of $P(k)$ on the scales accessible to Lyα forest measurements is sensitive to the global neutrino content, as free streaming by relativistic neutrinos in the early Universe suppresses power compared to models with only cold dark matter. This fact was used to put an upper limit (95% confidence) of 5.5 eV on m_ν.

Future work on measuring $P(k)$ from the Lyα forest will benefit from the huge data samples available from the Sloan Digital Sky Survey (Hui et al. in preparation). Different approaches to the problem of continuum fitting have been devised (e.g., Hui et al. 2000), so that measurements can be extended to scales an order of magnitude larger than at present. A larger number of spectra will also mean a greater space density, so that cross-clustering of adjacent spectra can be carried out, enabling us to have a true 3 dimensional view of clustering (see Viel et al. 2001, Pichon et al. 2001). On the theoretical side, it will be important to simulate large volumes, and improve our understanding of other influences on the Lyα forest, such as quasar radiation inhomogeneities (e.g., Gnedin 2000) and galaxy outflows which may ultimately limit the accuracy of these techniques.

4. COSMIC GEOMETRY

A way of measuring cosmic geometry was devised by Alcock and Paczynski (1979), which involves comparing the angular size of an object with its size in redshift units along the line of sight. Although no suitable distinct objects exist, it is possible to apply the test in a statistical sense to clustering measures such as the correlation function, which should be isotropic. In practice, peculiar velocities, which squash the clustering along the line of sight need to be modelled, which can only be done well on large scales, in the linear regime. Surveys of high redshift galaxies, or quasars which aim to apply this test must therefore be very large, in order that there be signal to measure on these large scales. The 2dF QSO redshift survey, which contains over 10,000 quasars at present has proven too small for a good measurement of cosmic geometry to be made (Outram et al. 2001).

The Lyα forest, on the other hand has been proposed as useful for carrying out this test, as the weakly non-linear densities involved mean that smaller scales can be used. Calculations by McDonald & Miralda-Escude (1999), and Hui, Stebbins & Burles (1999) indicate that spectra of as few as $10-20$ pairs of quasars separated by an arcminute may yield a measurement of cosmic geometry (for example differentiating an Einstein-de Sitter model from the now popular cosmological constant dominated model at 95 % confidence). Whether this test will ultimtely yield results will depend on whether enough pair of quasars are found (the SDSS should provide them), and also on whether the effects of peculiar velocity distortions can be modelled adequately.

5. OTHER COSMOLOGICAL INFORMATION

Studying statistical properties of the forest can also tell us about structure formation and help us prove whether or not gravitational instability was the dominant mechanism. Some approaches to extracting this sort of information include the inversion technique of Nusser and Haehnelt (1999,2000) who have shown that the probability distribution of mass fluctuations on the Jean's scale can be recovered from Lyα forest spectra. Gaztañaga & Croft 1999 compared moments of the flux in spectra with predictions of perturbation theory. In principle, gravtiational instability and the fluctuating Gunn-Peterson model for the Lyα forest make specific predictions for these moments which it should be possible to test observationally. The theoretical model also makes specific predictions for the way in which clustering on small and large scales is related. Zaldarriaga et al. (2000b) have developed an analysis technique based on this fact which was used to place tight limits on any possible non gravitational contribution to the growth of Lyα forest structure.

6. SUMMARY

The key to the usefulness of the Lyα forest as a cosmological probe is the simplicity of the dominant physical processes involved. Unlike many relationships in astronomy, which are only known empirically, with the Lyα forest we have a working theoretical model for the structure of the low density IGM which explains Lyα forest observations very well.

With this theory, we are able to derive the relation between an observed quantity, the flux in a spectrum pixel, and the matter density at a point in space. Once we have this, we can infer cosmological information from the observations. The mean level of absorption in the spectra can yield the baryonic matter density. Measurement of fluctuations in the absorption can be translated into fluctuations in the underlying matter field. A measurement of the linear power spectrum of mass fluctuations on scales of $\sim 1-10\ h^{-1}$Mpc follows (the only measurement so far on these scales). It should soon be possible to extend this measurement to scales 10 times larger or more using the data from the Sloan Digital Sky Survey. Using the now common technique of combining information from several sources, it is possible to use the Lyα forest in concert with CMB and cluster abundance measurements to derive a value for such parameters as the overall matter density (Ω_M), and the neutrino mass m_ν.

REFERENCES

Alcock, C. & Paczynksi, B., Nature, 281, 358
Bi, H.G. 1993, ApJ, 405, 479
Cen, R., Miralda-Escudé, J., Ostriker, J.P., & Rauch, M. 1994, ApJ,437, L9
Croft, R.A.C., Weinberg, D.H., Katz, N., & Hernquist, L. 1998, ApJ, 495, 44.
Croft, R.A.C., Hu, W., & Davé, 1999a, Phys. Rev. Lett., 83, 1092.
Croft, R.A.C., Weinberg, D.H., Pettini, M., Hernquist, L. & Katz, N., 1999b, ApJ, 520, 1 .
Croft, R.A.C., et al. 2001, ApJ, submitted, astro-ph/0012324
Gaztañaga, E., & Croft, R.A.C., 1999, MNRAS, 309, 885
Gnedin, N. Y., 2000, ApJ, in press, astro-ph/9909383
Gunn, J.E., & Peterson, B.A. 1965, ApJ, 142, 1633
Haehnelt, M.G., Madau, Piero, Kudritzki, Rolf, Haardt, Francesco 2001, ApJ, 549, L151
Hernquist L., Katz N., Weinberg D.H., & Miralda-Escudé J. 1996, ApJ, 457, L5

Hui, L., & Gnedin, N. 1997, MNRAS, 292, 27
Hui, L., Haiman, Z., Zaldarriaga, M., Alexander, T., 2001, ApJ, submitted, astro-ph/0104442
Hui, L., Stebbins, A., & Burles, S. 1999, ApJ, 511, L5
Hui, L., Burles, S., Seljak, U., Rutledge, R., Magnier, E., Tytler, D., 2000, ApJ, submitted, astro-ph/0005049
McDonald, P. & Miralda-Escudé, J. 1999, ApJ, 518, 24
McDonald P., Mirald-Escudé J., Rauch M., Sargent W., Barlow T., Cen R., Ostriker J.P. 2000, ApJ, 543, 1
Novosyadlyj, B., Durrer, R., Gottloeber, S., Lukash, V.N., Apunevych, S., A&A, 2000, 356, 418
Nusser, A., & Haehnelt, M., 1999, MNRAS, 303, 179
Nusser, A., & Haehnelt, M., 2000, MNRAS, 313, 364
Outram, P.J., et al. 2001, MNRAS submitted, astro-ph/0106012
Phillips, J., Weinberg, D.H., Croft, R.A.C., Hernquist, L., Katz, N., & Pettini, M. 2001, ApJ, in press, astro-ph/0001089
Pichon, C., Vergeley, J.L., Rollinde, E., Colombi, S., & Petitjean, P., 2001, MNRAS, submitted, astro-ph/0105196
Rauch, M., Miralda-Escudé, J., Sargent, W. L. W., Barlow, T. A., Weinberg, D. H., Hernquist, L., Katz, N., Cen, R., & Ostriker, J. P. 1997, ApJ, 489, 7
Rauch, M., 1998, ARAA, 36, 267
Steidel, C.C., Pettini, M., & Adelberger, K. L., 2001, ApJ, 546, 665
Viel,M., Matarrese, S., Mo, H.J., Haehnelt, M. & Theuns, T., 2001, MNRAS, submitted, astro-ph/0105233
Wang, X., Tegmark, M., Zaldarriaga, M. 2001, PRD, submitted, astro-ph/0105091
Weinberg, D.H., Croft, R.A.C., Hernquist, L., Katz, N., & Pettini, M. 1999, ApJ, 522, 563
Zaldarriaga, M., Hui, L., & Tegmark, M. 2000a, ApJ, submitted, astro-ph/0011559
Zaldarriaga, M., Seljak, U., & Hui, L. 2000b, ApJ, submitted, astro-ph/0007101
Zhang Y., Anninos P., & Norman M.L. 1995, ApJ, 453, L57