Constraining the dark energy with Ly-α forest

Uroš Seljak, Rachel Mandelbaum, Patrick McDonald

1 Department of Physics, Princeton University, Princeton NJ USA

Abstract.
Statistical properties of gas absorption in high redshift quasars such as power spectrum and bispectrum allow one to determine the evolution of structure over the redshift range $2 < z < 4$. Sloan Digital Sky Survey (SDSS) will measure around 10,000 quasar spectra in this redshift range and will allow one to determine the growth factor with a few percent accuracy. This allows one to extend the studies of dark energy to high redshift and determine the presence of dark energy if $\Omega_{\text{de}} > 0.1 - 0.2$ at $z > 2$. In combination with low redshift studies one can place useful limits on the time evolution of the equation of state.

1 Introduction

The study of the Ly-α forest has been revolutionized in recent years by the high resolution measurements using Keck HIRES spectrograph and by the development of theoretical understanding using hydrodynamical simulations and analytical models. The picture that has emerged from these studies is one where the neutral gas responsible for the absorption is in a relatively low density, smooth environment, which implies a simple connection between the gas and the underlying dark matter. The neutral fraction of the gas is determined by the interplay between the recombination rate (which depends on the temperature of the gas) and ionization caused by ultraviolet photons, the so called UV background. Photoionization heating and expansion cooling cause the gas density and temperature to be tightly related, except where mild shocks heat up the gas. This leads to a tight relation between the absorption flux and the gas density. Finally, the gas density is closely related to the dark matter density on large scales, while on small scales the effects of thermal broadening and Jeans smoothing have to be included. In the simplest picture described here all of the physics ingredients are known and can be modelled. In practice, the nonlinear physics requires the use of hydrodynamic simulations with sufficient dynamic range which are only now becoming available.

In the past couple of years cosmological observations such as redshift-luminosity relation from supernovae and position of the acoustic peaks in cosmic microwave background (CMB) combined with local matter density estimates have revealed the presence of another component in the universe, the so called dark energy. This component has negative pressure and the recent constraints indicate that $w = p/\rho \sim -1$. However, at the moment direct constraints are still allowing for a significant range in $w$, specially if it is allowed to vary in time. Many models have been proposed where $w$ either increases or decreases with redshift (some of these are discussed in these proceedings).
Theoretical studies have been performed on how to extract this evolution using low redshift probes. While statistical power for some of these planned or proposed experiments, such as SNAP using supernovae, LSST using weak lensing or optical, X-ray and Sunyaev-Zeldovich telescopes counting clusters, is truly impressive, the control of systematics is less well understood. For this reason it is important to have as many independent tests as possible.

One possibility that has not been discussed much so far is using Ly-α forest as a probe of dark energy. Since direct observations of quasars from the ground restrict one to the optical wavelengths ($\lambda > 3600\,\text{Å}$) one can only observe Ly-α forest for $z > 2$. If $w = -1$ independent of the redshift then if dark energy to dark matter density ratio $\Omega_{\text{de}}/\Omega_m = 2$ today the ratio will be below 0.1 at $z > 2$. In this case the growth factor will scale almost linearly with the scale factor just as in an Einstein-de Sitter universe and one cannot detect the presence of dark energy. On the other hand, if $w > -1$ either today or at a somewhat higher redshift then the decline of the dark energy fraction relative to dark matter is slowed down and dark energy can be dynamically important even at $z > 2$. In this case there will be deviations in the growth factor from the expected scaling that can be detected using the forest observations.

So far the only tests of the dark energy proposed have been using either the growth factor or the redshift luminosity distance. If one wishes to extract $w(z)$ then both of these involve a double integral over this quantity and degeneracies arise. A more direct and still in principle observable way is to measure the Hubble parameter $H(z)$, which is related to $w(z)$ through a single integral. One way to measure it is to have a characteristic feature which is fixed in comoving coordinates and observed in redshift space. The relation between redshift space and comoving space is the Hubble parameter itself and so observing the feature as a function of redshift provides $H(z)$ directly. The problem of course is that there are no characteristic features imprinted in large scale structure, since the distribution of structure in the universe is stochastic in nature. One must therefore look for a characteristic scale in correlations between structures. In principle such features could be provided by baryonic oscillations imprinted in the matter power spectrum, but in practice this is a weak effect limited to very large scales and so cannot be made very precise. One is thus left with the variations in the correlation function slope as a function of scale. It is well known that the power spectrum slope varies from $n \sim 1$ on large scales to $n \sim -3$ on small scales independent of redshift in CDM models. Hence the scale at which the slope takes a specific value can be viewed as a standard ruler and can be traced with redshift. If this slope is measured in redshift space, as is the case for either galaxy clustering along the line of sight or Ly-α forest correlations, then one is measuring directly $H(z)$. To be able to do this one has to detect the curvature in the slope over the dynamic range of observations. This is challenging, since the dynamic range is narrow and the error on the slope will be large. We will show below that such a detection should be possible with the current sample, but is not expected to improve the constraints on $w(z)$ significantly.
2 Error estimation

The basic approach to the error estimation is a standard one. Arranging the statistics one is estimating (in our case power spectrum and bispectrum) into a vector $x$ and the parameters one is interested in into vector $y$ the Fisher matrix is given by

$$F_{kl} = \left( \frac{dx}{dy_k} \right)^T \cdot C^{-1} \cdot \left( \frac{dx}{dy_l} \right),$$

(1)

where $C_{ij} = \langle (x_i - \langle x_i \rangle)(x_j - \langle x_j \rangle) \rangle$.

One must thus compute both the covariance matrix and the derivatives with respect to the parameters on the statistic than one is using. We have found that combining the bispectrum and the power spectrum information significantly improves the determination of the amplitude of fluctuations. The reason for this is a degeneracy between the mean flux absorption and the linear amplitude. Changing the mean flux changes the power spectrum of the flux significantly, as does the variation in the linear amplitude. The mean flux absorption is a free parameter, since it is governed by the amount of UV background that controls the fraction of neutral gas in ionizing equilibrium. While it can be determined directly using independent methods such as continuum fitting or principal component analysis of spectra, the precision of these methods is not sufficient to break the degeneracies entirely. However, at the 3-point function level gravity predicts a very specific pattern of correlations, which cannot be mimicked by the mean flux variation. A full analysis reveals that this can improve the precision of amplitude determination by a factor of 3.

To compute the covariance matrix of power spectrum and bispectrum we use hydro-PM simulations to simulate the forest, apply the analysis on many realizations of the simulations and compute the mean and covariance matrix of the statistics. We use power spectrum and bispectrum information for $10^{-3} s/km < k < 2 \times 10^{-2} s/km$, which is the range of interest for the SDSS data. We then vary by small amounts the parameters of interest one at a time, rerun the simulation with the same initial conditions to minimize the sampling variance and recompute the mean. This allows us to compute the derivatives $dx_i/dy_j$ of the statistic $x_i$ with respect to the parameter $y_j$. The parameters we vary are the amplitude of fluctuations as a function of redshift (we use 9 bins between $2.2 < z < 3.8$), mean flux as a function of redshift, slope and curvature of the primordial spectrum and temperature density relation parametrized as a power law with amplitude and slope as the parameters, both of which can vary with redshift.

The assumed redshift distribution of the sample mimics the SDSS distribution in the current data. We have scaled the length of the forest to match the overall number of quasars to 3000, which is significantly less than the final sample of around 10,000 QSOs. Our results are thus conservative and will be improved significantly in the future, assuming that systematic errors can
be kept under control. We assume the spectra have signal to noise of 5 and resolution of 70km/s, which is typical of the SDSS spectra. Neither signal to noise nor resolution are particularly critical in this application, since one is mostly interested in large scale correlations where other parameters such as the temperature of the gas or the density temperature relation do not play a major role.

3 Dark energy constraints

To study the dark energy parameters we project the Fisher matrix to fewer parameters, parametrizing the growth factor evolution in terms of $\Omega_{de}$ and $w(z)$. For the redshift evolution we limit ourselves to constant and linear evolution models, $w_q = w_0 + w_1(a - 1)$. The density in dark energy and equation of state are degenerate if one only uses information from Ly-α forest. This is not surprising, since the redshift range probed is too small to determine two parameters from the growth factor evolution (as mentioned above, we find that $H(z)$ information does not provide any additional constraints). In the following we fix $\Omega_{de}$ and present errors on equation of state only. The motivation for this is that other tests, most notably CMB combined with large scale structure tests (e.g. cluster counts, galaxy clustering, weak lensing), will be able to determine $\Omega_{de}$ at $z = 0$ very accurately. If these tests also provide independent constraints on $w_0$ then for the time dependent $w$ one can use our results to constrain $w_1$.

Since the sensitivity to the dark energy depends strongly on the amount of dark energy at $z > 2$ it is clear that the errors will depend strongly on the assumed values of $\Omega_{de}$ and $w(z)$. For the models studied here their values are given in table 1. The table also shows the errors on $w_0$ assuming fixed $\Omega_{de}$ (and $w_1$ in time dependent models) and errors on $w_1$ assuming fixed $\Omega_{de}$ and $w_0$. The errors are marginalized over all the other parameters. One can see that the limits improve if $w_0$ is more positive or if $w_1$ is significantly negative, since the dark energy is then more important at higher redshift. Of particular interest are the limits on time dependent $w$. For example, in models 7 and 8 we assume today $w_0 = -0.8$, which increases to $w = -0.4$ and $w = -0.2$ at $z=2.6$, respectively. In such models the error on $w_1$ is 0.2, which makes them distinguishable at $1.5\sigma$ with the current sample and $3\sigma$ with the full sample, assuming that both $\Omega_{de}$ and $w_0$ can be accurately determined with the other methods. These errors improve further if we live in a universe with lower matter density than $\Omega_m = 0.33$ assumed here.

While there is no simple single parameter combination that describes the sensitivity to dark energy it is clear that the precision is correlated with $\Omega_{de}$ at $z = 2.6$. Our results show that if $\Omega_{de}(z = 2.6) > 0.2$ then the deviations in the growth factor are sufficiently large to be detected in Ly-α forest spectra using the current SDSS sample. With the full SDSS sample this limit can be improved further and models with $\Omega_{de}(z = 2.6) > 0.1$ should be detectable.
Table 1: Parameters and error bounds for dark energy models, where $w_q = w_0 + w_1(a - 1)$. The errors are marginalized over all the other parameters except dark energy ones (see text for details).

| Model | $\Omega_q,0$ | $\Omega_q(z = 2.6)$ | $w_0$ | $w_1$ | $\sigma_{w_0}$ | $\sigma_{w_1}$ |
|-------|--------------|---------------------|-------|-------|---------------|---------------|
| 1     | 0.67         | 0.12                | -0.7  | 0.0   | 0.22          | -             |
| 2     | 0.85         | 0.28                | -0.7  | 0.0   | 0.09          | -             |
| 3     | 0.49         | 0.06                | -0.7  | 0.0   | 0.36          | -             |
| 4     | 0.67         | 0.04                | -1.0  | 0.0   | 0.36          | -             |
| 5     | 0.67         | 0.30                | -0.4  | 0.0   | 0.17          | -             |
| 6     | 0.67         | 0.12                | -0.8  | -0.2  | 0.12          | 0.31          |
| 7     | 0.67         | 0.19                | -0.8  | -0.5  | 0.09          | 0.22          |
| 8     | 0.67         | 0.27                | -0.8  | -0.8  | 0.068         | 0.18          |
| 9     | 0.67         | 0.09                | -1.0  | -0.5  | 0.16          | 0.41          |

While this is still not sufficiently accurate to measure dark energy directly for cosmological constant model ($w = -1$) $\Omega_m \sim 0.3$, it will provide important constraints on the more general models of dark energy such as the tracker models, where equation of state naturally increases in value at higher redshifts.