Detection of Ly\(\beta\) auto-correlations and Ly\(\alpha\)-Ly\(\beta\) cross-correlations in BOSS Data Release 9

Vid Iršič, Anže Slosar, Stephen Bailey, Daniel J. Eisenstein, Andreu Font-Ribera, Jean-Marc Le Goff, Britt Lundgren, Patrick McDonald, Ross O’Connell, Nathalie Palanque-Delabrouille, Patrick Petitjean, Jim Rich, Graziano Rossi, Donald P. Schneider, Erin S. Sheldon, Christophe Yèche

\(^a\)Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia
\(^b\)Brookhaven National Laboratory, Blgd 510, Upton NY 11375, USA
\(^c\)Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
\(^d\)Harvard-Smithsonian Center for Astrophysics, MS #20, 60 Garden St., Cambridge, MA 02138, USA
\(^e\)Institute of Theoretical Physics, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
\(^f\)CEA, Centre de Saclay, IRFU, F-91191 Gif-sur-Yvette, France
\(^g\)Department of Astronomy, University of Wisconsin, 475 North Charter Street, Madison, WI 53706, USA
\(^h\)Physics Department, Carnegie Mellon University, Pittsburgh, PA 15213, USA
\(^i\)Université Paris 6 et CNRS, UMP7095, Institut d’Astrophysique de Paris, 98bis Boulevard Arago, 75014 Paris, France
\(^j\)Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA
\(^k\)Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA
Abstract. The Lyman-β forest refers to a region in the spectra of distant quasars that lies between the rest-frame Lyman-β and Lyman-γ emissions. The forest in this region is dominated by a combination of absorption due to resonant Lyα and Lyβ scattering. When considering the 1D Lyβ forest in addition to the 1D Lyα forest, the full statistical description of the data requires four 1D power spectra: Lyα and Lyβ auto-power spectra and the Lyα-Lyβ real and imaginary cross-power spectra. We describe how these can be measured using an optimal quadratic estimator that naturally disentangles Lyα and Lyβ contributions. Using a sample of approximately 60,000 quasar sight-lines from the BOSS Data Release 9, we make the measurement of the one-dimensional power spectrum of fluctuations due to the Lyβ resonant scattering. While we have not corrected our measurements for resolution damping of the power and other systematic effects carefully enough to use them for cosmological constraints, we can robustly conclude the following: i) Lyβ power spectrum and Lyα-Lyβ cross spectra are detected with high statistical significance; ii) the cross-correlation coefficient is ≈ 1 on large scales; iii) the Lyβ measurements are contaminated by the associated OVI absorption, which is analogous to the SiIII contamination of the Lyα forest. Measurements of the Lyβ forest will allow extension of the usable path-length for the Lyα measurements while allowing a better understanding of the physics of intergalactic medium and thus more robust cosmological constraints.

Keywords: cosmology, Lyβ forest, Lyα forest, large scale structure
1 Introduction

Lyman-α forest is a series of absorption lines, blue-ward of the Lyα emission in the spectra of high-redshift quasars. Although it was discovered nearly half a century ago [23], it only recently became a useful cosmological probe [40, 41]. An important part in this evolution was due to the technological progress that made it possible for large surveys such as Sloan Digital Sky Survey (SDSS, [1, 2, 4–6, 10, 12, 13, 16, 18, 20–22, 29, 31, 33, 36, 42]) to measure spectra of quasars reliably and in large numbers.

The physical picture of the Lyα forest was established in the 1990s. The absorption features primarily arise in the near-mean density regions [3, 7, 43] from the weakly non-linear fluctuations of gas held in equilibrium by photo-ionizing background radiation [19, 39]. This makes it possible for the Lyα forest fluctuations to be predicted from first principles using large numerical simulations. Namely, the complicated astrophysics of fluid dynamics, baryon-condensation, star-formation and feedback due to supernova and active galactic nuclei activity is absent - a typical line of sight does not pierce through a virialized object, and when it does, it results in a complete absorption which makes the detailed modeling of virialized regions inessential. Even though, the effect of astrophysics cannot be completely neglected and has some impact on flux statistics ([28, 37]), the effect for Lyα absorption is small and can be largely neglected for quantitative studies. In particular [37] shows that the effect of feedback from active galactic nuclei and supernovae falls off rapidly towards higher redshifts at which our measurements are taken and is of the order of a percent. While this makes predictions of Lyα quantities considerably easier than a-priori galaxy evolution, the physics of intergalactic medium (IGM) remains complicated and any results must be cross-checked in as many different ways as possible.

The field has settled on using the one-dimensional power spectrum $P_F(k, z)$ of the relative fluctuations in the transmitted flux fraction $\delta_F$ as the quantity of choice when comparing observations with the theoretical predictions[8, 9, 25, 26, 28, 38]. The main reason for this
selection is that the power spectrum of transmitted flux fluctuations is observationally closest
to the data: it is essentially an appropriately scaled version of the actual fluctuations in the
observed forest and hence it is easy to understand the systematics and the noise properties of
the measurement. Choosing the power spectrum over the correlation function more cleanly
decouples the scales involved. For example, fluctuations due to poor understanding of the
continuum are restricted to large scales.

Recently, the three-dimensional correlations have been measured in the Lyα forest ([6,
34, 35]) and it may eventually be possible to make a unified analysis of both 1D and 3D
correlations. However, systematic issues are very different in the two cases and at present
the 1D power spectrum of fluctuations is our best approach for measuring the linear power
spectrum amplitude at scales around $k \sim 1 h/\text{Mpc}$.

As discussed above, systematic control of astrophysical and instrumental effects remains
one of the largest challenges in the Lyα studies. There are two main ways to independently
measure the properties of the IGM and thus cross-check the assumptions. The first one is to
use a higher order statistic (bispectrum or trispectrum, [17, 24, 28]). This approach allows
one to measure essentially the same quantities as in the power spectrum with a similar signal-
to-noise, but with largely independent or differently-scaling systematics. An alternative is to
use higher order Lyman absorption, which was proposed in [11] and which we study in this
work.

Understanding the Lyβ forest would be useful in several ways. First and foremost,
the Lyβ forest probes the same hydrogen gas, but with a smaller optical depth at a given
column density of gas. Fortunately, there is no uncertainty in the ratio of optical depths,
since it is entirely determined by atomic physics. The ratio of cross sections for Lyman series
lines simplifies to the ratio of oscillator strength for those lines, which can be calculated
analytically. The oscillator strength of Lyman transition of order $n$ is given by ([32])

$$f_n = 2^8 n^5 \frac{(n - 1)^{2n-4}}{3(n + 1)^{2n+4}}. \tag{1.1}$$

The ratio of the optical depths for β and α lines $r_{βα}$ is thus given by

$$r_{βα} = \frac{τ_β}{τ_α} = \frac{f_3}{f_2} \approx 0.1901. \tag{1.2}$$

Given that $r_{βα}$ is of $O(1)$ (rather than $\ll 1$) means that we are probing somewhat larger gas
densities, but that the dominant physics is the same and the numerical simulations made for
Lyα will likely suffice. While virialized regions are still going to result in complete absorption,
the Lyβ forest will likely be affected more by the effects of the galactic feedback (although
this will need to be checked using numerical simulations in further work) and other nuances
of the IGM physics. Therefore, when used in conjunction with the Lyα absorption, Lyβ
information can break degeneracies in modeling of these regions.

At the same time, the absorption in the Lyβ region of the forest is dominated by the
Lyα absorption. Therefore, if one is able to simultaneously model the Lyα and Lyβ regions,
it is possible to extend the useful path length for Lyα forest by up to 20% (depending on
the redshift distribution of quasars in a given survey). This can, for example, significantly
increase the sensitivity to the baryon acoustic oscillations signal, without any increase in the
cost of an experiment.

The purpose of this paper is to make a proof-of-concept measurement of the Lyβ forest
in the DR9 data release of Baryon Oscillation Spectroscopic Survey (BOSS; [4, 10]), which
is part of the Sloan Digital Sky Survey III collaboration ([12, 16, 18, 20, 36, 42]). We believe our detection significance is robust and the results are correct and consistent with expectations. However, these measurements should not be used to constrain cosmological parameters: our understanding of the resolution uncertainty, noise bias and other subtleties is limited. Moreover, the results are strong enough to show that these measurements are clearly feasible with high precision. For example, even with our limited understanding of systematics, we are able to measure a contaminating metal line in the Ly$\beta$ forest with percent level accuracy on its wavelength and identify it as the OVI feature.

The paper is structured as follows. In Section 2 we present the theoretical description of the fluctuations and how physically relevant quantities can be derived from the data. The data and simulations used are discussed in Section 3. In Section 4 we present the results on the mock data and in Section 5 we show the final measurements on the data. We conclude in Section 6.

2 Description of the Ly$\alpha$ and Ly$\beta$ forests

2.1 Power spectra of fluctuations

The spectrum for a quasar $q$ at an observed wavelength $\lambda_o$ is given by

$$f^q(\lambda_o) = C^q(\lambda_r)F^q(\lambda_o), \quad (2.1)$$

where $C^q(\lambda_r)$ is the intrinsic quasar spectrum (observed by an observer in the rest frame of the quasar with redshift $z_q$, where $\lambda_r = \lambda_o/(1 + z_q)$) and $F(\lambda_o)$ is the total absorption due to absorbing material along the line of sight to the quasars

$$F^q(\lambda_o) = \prod_{i, (z_i < z_q)} e^{-\tau^q_i(r = c\ln\lambda_o/\lambda_i)}, \quad (2.2)$$

where $\tau^i$ is the optical depth for the $i$-th component absorbing at rest-frame $\lambda_i$ and $c$ is speed of light. Optical depth is a function of distance, which we parametrise in terms of the logarithm of the observed wavelength. The reason for this choice is that the difference in this distance measure is expressed in the usual units of kms$^{-1}$. The crucial point is that for a given observed-frame wavelength, we allow for several absorbers that occupy different positions along the line of sight to the quasar. Of course, since matter behind the quasar cannot absorb light, any given component can absorb only at sufficiently small observed wavelengths. In other words, Ly$\alpha$ absorption can be found blue-ward of the rest-frame Ly$\alpha$ emission, the Ly$\beta$ absorption blue-ward of the rest-frame Ly$\beta$ emission, etc.

In Ly$\alpha$ forest studies, it is usually assumed that the Ly$\alpha$ absorption is the dominant source of absorption and worked in terms of the relative transmitted flux fluctuations

$$F^q(\lambda_o) = e^{-\tau^q} = \bar{F}\alpha(r^\alpha)(1 + \delta^q(\alpha)), \quad (2.3)$$

where $r^\alpha = c\ln\lambda_o/\lambda_\alpha$ is our radial coordinate. We therefore describe the fluctuations in the forest as relative fluctuations around the mean absorption. The mean of those fluctuations is $\langle \delta^q \rangle = 0$ and the two point function is conveniently described in terms of the correlation function $\xi_{\alpha\alpha}(x, z)$

$$\langle \delta_\alpha(r_1^\alpha)\delta_\alpha(r_2^\alpha) \rangle = \xi_{\alpha\alpha}(x = r_2^\alpha - r_1^\alpha = \ln \lambda_2/\lambda_1, \bar{z}). \quad (2.4)$$
or equivalently the power spectrum
\[ \xi_{\alpha\alpha}(x, \bar{z}) \equiv \frac{1}{2\pi} \int_{-\infty}^{\infty} P_{\alpha\alpha}(k, \bar{z}) e^{-kx} dk = \frac{1}{\pi} \int_{0}^{\infty} P_{\alpha\alpha}(k, \bar{z}) \cos(kx) dk, \] (2.5)
where \( \bar{z} \) is defined as
\[ 1 + \bar{z} = \frac{\sqrt{\lambda_1 \lambda_2}}{\lambda_\alpha}. \] (2.6)

Here and henceforth in this paper \( \lambda_1 \) and \( \lambda_2 \) are observed wavelengths (\( \lambda_o \)) at two different positions in the quasar spectrum. They should not be confused by rest-frame wavelength \( \lambda_i \) from Equation 2.2 which is, in this work, replaced by \( \lambda_{\alpha} \) rest-frame absorption wavelength \( \lambda_{\alpha} = 1215.67\text{Å} \) and \( \lambda_{\beta} \) rest-frame absorption wavelength \( \lambda_{\beta} = 1025.72\text{Å} \).

The power spectrum in Equation 2.5 is consistent with standard definitions found elsewhere in the literature [8, 27, 38].

We proceed by adding the absorption by the \( \lambda_{\beta} \) line. In this case, where considering a pixel in the \( \lambda_{\beta} \) forest, we have
\[ P^q(\lambda_o) = e^{-\tau_{\alpha}^q - \tau_{\beta}^q} = \bar{F}_\alpha(z_\alpha) \bar{F}_\beta(z_\beta)(1 + \delta_\alpha^q(r_\alpha))(1 + \delta_\beta^q(r_\beta)) = \bar{F}_T(\lambda_o)(1 + \delta_T(\lambda_o)). \] (2.7)

Any given pixel in the \( \lambda_{\beta} \) forest thus receives a contributions to the absorption from gas residing at two distinct redshifts. One can distinguish between the two components only statistically, by observing the total relative fluctuation \( \delta_T \) and cross-correlating it with other fluctuations in the \( \lambda_{\alpha} \) and \( \lambda_{\beta} \) forests (see section 2.3). The two-point function of the \( \lambda_{\beta} \) forest is given by Equations (2.4) and (2.5). The cross-power is slightly more subtle:
\[ \langle \delta_\alpha(r_1^\alpha) \delta_\beta(r_2^\beta) \rangle = \xi_{\alpha\beta} \left( x = r_2^\beta - r_1^\alpha = \ln \left( \frac{\lambda_1/\lambda_\beta}{\lambda_1/\lambda_\alpha} \right), \bar{z}_{\alpha\beta} \right), \] (2.8)
where \( \bar{z}_{\alpha\beta} \) is defined as
\[ 1 + \bar{z}_{\alpha\beta} = 1 + \bar{z}_{\beta\alpha} = \sqrt{\frac{\lambda_1 \lambda_2}{\lambda_\alpha \lambda_\beta}}. \] (2.9)

It is evident from this definition that
\[ \xi_{\alpha\beta}(x, \bar{z}) = \xi_{\beta\alpha}(-x, \bar{z}) \neq \xi_{\alpha\beta}(-x, \bar{z}), \] (2.10)
since for absorption by two clouds of gas at mean redshift \( \bar{z}_{\alpha\beta} \), the expectation value of the correlation is different for the case of a lower-redshift cloud absorbing in \( \alpha \) and a higher redshift cloud absorbing in \( \beta \) or vice-versa. As a result, the correlation function is not symmetric around zero and the cross-power spectrum has both real and imaginary components:
\[ \xi_{\alpha\beta}(x, \bar{z}, \bar{\bar{z}}) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left[ P_{\alpha\beta}(k, \bar{z}) + i Q_{\alpha\beta}(k, \bar{z}) \right] e^{-ikx} dk. \] (2.11)

There exists no apriori argument that the imaginary part of the cross-power spectrum should be zero. Since a non-zero \( Q_{\alpha\beta} \) reflects a non-symmetric problem it must be studied for each specific case separately. In the next subsection we elaborate why a non-zero \( Q_{\alpha\beta} \) is expected in \( \lambda_{\alpha}-\lambda_{\beta} \) correlations.

A complete statistical description of \( \lambda_{\alpha} \) and \( \lambda_{\beta} \) fluctuations at the two-point level is thus given by four power spectra \( P_{\alpha\alpha}, P_{\beta\beta}, P_{\alpha\beta}, Q_{\alpha\beta} \). Each of these is a function of scale and redshift.
2.2 Theoretical expectation for $P_{\beta\beta}$, $P_{\alpha\beta}$ and $Q_{\alpha\beta}$

Before proceeding, let us briefly discuss the expected quantities to be measured by the new power spectra.

First, the reader might be confused as to whether the new quantities are truly linearly independent, since in the introduction we have argued that the ratio of the optical depths is deterministic and known from atomic physics. Indeed, they are independent for the following reasons. Fluctuations in the optical depth are related to the fluctuations in the transmitted flux fraction via a non-linear transformation

$$\tilde{F}(1 + \delta_F) = e^{-\bar{\tau}(1+\delta_\tau)} = e^{-\bar{\tau}(1 - \bar{\tau}\delta_\tau + \frac{1}{2} \bar{\tau}^2 \delta_\tau^2 + \ldots)}.$$ (2.12)

We immediately see that $\bar{\tau} \neq e^{-\bar{\tau}}$, since even zero-lag correlators contribute to the mean. Therefore, while $\bar{\tau}_\beta = r_{\beta\alpha} \bar{\tau}_\alpha$, it is not possible to write a similar relation between $\bar{\tau}_\alpha$ and $\bar{\tau}_\beta$. By the same token, any 2-point statistics in $\delta_F$ will contain contributions not just from the 2-point statistics of $\delta_\tau$, but also all higher-order correlators and hence one cannot write relations between $P_{\alpha\alpha}$ and, for example, $P_{\beta\beta}$.

We do know, however, that on very large scales in three-dimensions, both absorptions become linear tracers of the underlying density field. Consequently one expects the 3D cross-correlation coefficient to be close to unity

$$r_{3D}(k) = \frac{P_{3D,\alpha\beta}(k)}{\sqrt{P_{3D,\alpha\alpha}(k)P_{3D,\beta\beta}(k)}} \sim 1 \text{ for small } k.$$ (2.13)

Of course, due to stochasticity in the biasing relation (taking form of white noise in the low $k$ limit), the cross-correlation coefficient will be somewhat less than unity, but this effect is expected to be small (the absorption is, after all, coming from exactly the same structure along each line of sight).

More importantly, however, the 1D power spectrum aliases small-scale three-dimensional modes into large scale one-dimensional modes

$$P_{1D}(k) = \frac{1}{2\pi} \int_k^\infty P_{3D}(k')k'dk'.$$ (2.14)

Therefore the cross-correlation coefficient between $\text{Ly}\alpha$ and $\text{Ly}\beta$ 1D power spectra, defined as

$$r = \left[ \frac{P_{\alpha\beta}^2(k) + Q_{\alpha\beta}^2(k)}{P_{\alpha\alpha}(k)P_{\beta\beta}(k)} \right]^{1/2},$$ (2.15)

is expected to be somewhat smaller than unity, but one would not expect $r \ll 1$ at small $k$.

Finally, in a non-evolving universe, $Q_{\alpha\beta} = 0$. The real Universe is evolving, but sufficiently slowly so that for small separations the approximation of stationary statistics is in general accurate. Hence, we expect $Q_{\alpha\beta}$ to be smaller than $P_{\alpha\beta}$, i.e., the cross-power spectrum to be approximately real. However, $Q_{\alpha\beta}$ is required for a statistically consistent complete description of fluctuations in a given spectrum and thus it should be measured together with other quantities.
Figure 1. Geometry of the absorption in the $\alpha$ and $\beta$ forests. A “cloud” of gas absorbing at redshift $z_3$ in Ly$\alpha$ is also absorbing in the Ly$\beta$ forest. However, the same pixel in the Ly$\beta$ forest is also subject to absorption by another “cloud” at redshift $z_1$. Ditto for clouds at $z_4$ and $z_2$. When cross-correlating two pixels residing in the $\beta$ region of the quasar spectrum, one must take into account four contributions to the correlations. When cross-correlating a pixel in the Ly$\beta$ forest with one in the Ly$\alpha$ forest, one must take into account two correlations.

2.3 Measuring power spectra from the data

We proceed by discussing the reconstruction of these power spectra from the data. The $P_{\alpha\alpha}$ can be extracted relatively directly, but other components are more difficult, because $\beta$ absorption is always contaminated by the lower redshift $\alpha$ absorption.
The model that we use for the observed quasar spectrum is given by:

\[ f^q(\lambda_i) = A^q \bar{C}(\lambda_i^{\text{rest}}) \bar{F}_T(z_i) (1 + \delta_T(\lambda_i)). \]  

(2.16)

The continuum in each quasar \( C^q(\lambda_r) \) is modeled by a quasar amplitude \( A^q \) and the mean continuum \( \bar{C}(\lambda_i^{\text{rest}}) \). The absorption field is decomposed into a mean absorption

\[ \bar{F}_T = \begin{cases} 
\lambda_r > \lambda_\alpha & 1 \\
\lambda_\alpha > \lambda_r > \lambda_\beta & F_\alpha(z) \\
\lambda_\beta > \lambda_r & F_\alpha(z) F_\beta(z)
\end{cases} \]  

(2.17)

and fluctuations

\[ 1 + \delta_T = \begin{cases} 
\lambda_r > \lambda_\alpha & 1 \\
\lambda_\alpha > \lambda_r > \lambda_\beta & 1 + \delta_\alpha \\
\lambda_\beta > \lambda_r & (1 + \delta_\alpha)(1 + \delta_\beta)
\end{cases} \]  

(2.18)

In this work, we ignore the second order contributions in the Ly\( \beta \) forest

\[ \delta_T(\lambda_\alpha) = \delta_\alpha(\lambda_\alpha) + \delta_\beta(\lambda_\beta) + \delta_\alpha(\lambda_\alpha) \delta_\beta(\lambda_\beta) \]  

(2.19)

and thus work with effective fluctuations in the \( \beta \) forest

\[ \delta_\beta'(\lambda_\beta) = \delta_\beta(\lambda_\beta) + \delta_\beta(\lambda_\beta) \delta_\alpha(\lambda_\alpha). \]  

(2.20)

Note that while quadratic term cannot be neglected, because it is not small, it is for all practical purposes uncorrelated with the \( \beta \) forest as it corresponds to gas that is \( \sim 400 \text{ Mpc}/h \) away – on scales considerably larger than the largest scales on which we measure the power.
Figure 3. Power spectrum components measured on two different mock data sets: results with known quasar continua (solid line) and the full analysis (dashed line). This plot displays the mean of 10 realizations of 10000 QSO mock data set. No PSF deconvolution has been performed and hence the power drops to zero at large $k$ values.
Figure 4. Error correlation matrices $C_{ij} = C_{ij}/\sqrt{C_{ii}C_{jj}}$. Top row figures (a and b) are for estimator covariance matrix, while bottom row are for the bootstrap derived covariance matrix. The left side figures (a and c) are an expanded view of the sub-matrix at redshift $z = 2.8$ (upper left corner of the full matrix), while the right figures are the full matrices. The diagonal elements (unity) by definition were set to zero to increase the contrast. See text for discussion.

Using the definition of the Fourier transform between correlation function the power spectrum from Equation (2.5) the corrected power spectrum can be written as

$$P_{\beta\beta}'(k, z) = P_{\beta\beta}(k, z) + \frac{1}{2\pi} P_{\beta\beta}(k, z) * P_{\alpha\alpha}(k, z_a) = P_{\beta\beta}(k, z) + \frac{1}{2\pi} \int_{-\infty}^{\infty} P_{\beta\beta}(y, z) P_{\alpha\alpha}(k-y, z_a)dy,$$

(2.22)

where $(*)$ stands for convolution. Assuming $P_{\alpha\alpha}$ and $P_{\beta\beta}$ to be approximately white, i.e., $P_{\alpha\alpha}(k, z) = \sigma_{\alpha}^2(z)$, where $\sigma^2$ is the variance of the field, the correction to the cross correlation
The coefficient is
\[ r'_{\alpha\beta}(k,z) = r_{\alpha\beta}(k,z) \frac{1}{\sqrt{1 + \sigma^2_{\alpha}(z_\alpha)}} \approx r_{\alpha\beta}(k,z) \left( 1 - \frac{\sigma^2_{\alpha}(z_\alpha)}{2} \right). \] (2.23)

Since \( z_\alpha \) is always smaller than \( z \), for our highest measured redshift bin of \( z = 3.4 \), the corresponding \( z_\alpha \) would be \( z_\alpha = 2.74 \). The variance at \( z_\alpha = 2.74 \) is approximately \( \sigma^2_{\alpha}(2.74) = 0.08 \) ([34, 35]) and since the variance is increasing with redshift ([34, 35]) this is the largest correction we would be able to apply. Thus, since the correction to the cross-correlation coefficient is less than 5%, the effect is well below what we can currently measure. It is important to note, however, that this will need to be carefully modeled for the future precision observations.

Under these approximations, we now drop a prime on \( \delta_\beta \) and proceed with writing correlations between measured pixels in the spectrum. A correlation of one pixel in the Ly\( \beta \) forest with a pixel in the Ly\( \alpha \) forest is given by
\[ \langle \delta_\alpha(\lambda_1) \delta_T(\lambda_2) \rangle = \xi_{\alpha\alpha}(r^\alpha_2 - r^\alpha_1) + \xi_{\alpha\beta}(r^\beta_2 - r^\alpha_1) \] (2.24)
and a correlation of two pixels in the Ly\( \beta \) forest contains four terms
\[ \langle \delta_T(\lambda_1) \delta_T(\lambda_2) \rangle = \xi_{\alpha\alpha}(r^\alpha_2 - r^\alpha_1) + \xi_{\beta\beta}(r^\beta_2 - r^\beta_1) + \xi_{\alpha\beta}(r^\beta_2 - r^\alpha_1) + \xi_{\alpha\beta}(-r^\beta_1 + r^\alpha_2). \] (2.25)

This is illustrated schematically in the Figure 1.

In this study we work within an optimal quadratic estimator framework using the same methodology (and code-base) as in [35]. In particular, we model the power spectrum functions \( P \) and \( Q \) as flat power-bands measured in 20 bins, from \( k = 0.000445881 \) to \( k = 0.05 \) in steps of \( \log k = 0.1 \). The lowest \( k \) bin was extended to \( k = 0.05 \). In redshift-direction, we use uniformly-spaced redshift bins from \( z = 1.9 \) to \( z = 3.5 \) in steps of 0.2 and the model interpolates between values determined at those redshifts. For Ly\( \beta \) and the cross power spectrum we use redshift bins from \( z = 2.5 \) to \( z = 3.5 \). The redshift corresponds to the true gas redshift, so Ly\( \beta \) absorption from a clump of gas at \( z < 2.5 \) is shifted into UV and thus not recorded by the SDSS-III data. There is little signal in lowest and highest redshift bins, but due to interpolation, we can recover some information.

In this parametrisation, the Ly\( \beta \) forest receives linear contributions from all power spectrum bins. Even in the case of the usual Ly\( \alpha \) forest alone, however, a pair of pixels receives contributions from all power spectrum bins, and hence from the point of view of a quadratic estimator, our situation is not very different from the standard case.

In short, the basic data-analysis proceeds as follows:

- We start by measuring the mean continuum and absorption as described in [35]. This process has been extended to allow for an additional mean absorption in the \( \beta \) forest \( \bar{F}_\beta \), but is otherwise the same as [35].

- We then measure only Ly\( \alpha \) forest power spectrum using the mean continuum and absorption from above. This provides a good starting estimate when measuring all the power spectrum components.

- Lastly we measure all four power spectra \( P_{\alpha\alpha}, P_{\beta\beta}, P_{\alpha\beta}, Q_{\alpha\beta} \). This procedure is similar to the one described in [35] but extended to Ly\( \beta \) region.
2.4 Metal contamination at small velocity separations

In [28], it was found that absorption by SiIII contaminates the flux power spectrum measurement. SiIII absorbs at a wavelength 1206.50Å, which is close to the Lyα absorption wavelength, therefore SiIII “shadows” the Lyα correlations in the forest. In principle, one could treat the SiIII absorptions in exactly the same manner as the Lyβ absorptions - by writing a full model for this contamination.

While this is possible, it is certainly not easy, because any estimator will have a difficult time distinguishing between the two absorptions. The most likely result would be heavily correlated measurements between SiIII and Lyα power. Therefore, it is easier to treat the SiIII absorption as a small correction to the Lyα absorption.

We will later find a similar contamination issue in the Lyβ forest. Both contaminations leak power into $P_{\alpha\beta}$ and $Q_{\alpha\beta}$. Fortunately, the cross-correlations are able to distinguish between the relative signs of these absorptions.

We therefore develop a simple model with one contaminant in the Lyα forest and one dominant in the Lyβ forest.

The basic assumption of this model is that the fluctuations of the metal contaminant can be modeled as a scaled and shifted flux fluctuation field of the Lyα (or Lyβ) field [28]

$$\delta'_\alpha(x) = \delta_\alpha(x) + \delta_M(x) = \delta_\alpha(x) + a\delta_\alpha(x + v_\alpha).$$

As discussed in the Section 2.2, this approximation does eventually break down at some level of precision, but it does provide a good fit to the data. For a more detailed analysis of metal contaminations see [15].

This model of flux fluctuations yields the following power spectrum

$$P'_{\alpha\alpha}(k) = P_{\alpha\alpha}(k) \left[1 + a^2 + 2a \cos (kv_\alpha)\right],$$

and ditto for the Lyβ power spectrum contaminated with a metal of strength $b$ and frequency $v_\beta$.

In the cross-power spectrum, this model affects both the real and imaginary components of the cross power spectrum

$$P'_{\alpha\beta}(k) = n(k)P_{\alpha\beta}(k) + m(k)Q_{\alpha\beta}(k),$$

$$Q'_{\alpha\beta}(k) = n(k)Q_{\alpha\beta}(k) - m(k)P_{\alpha\beta}(k),$$

where the functions $n(k)$ and $m(k)$ are given by

$$n(k) = 1 + a \cos (kv_\alpha) + b \cos (kv_\beta) + ab \cos [k (v_\beta - v_\alpha)],$$

$$m(k) = a \sin (kv_\alpha) - b \sin (kv_\beta) - ab \sin [k (v_\beta - v_\alpha)].$$

The metal contaminant mixes the intrinsic real and imaginary part of the cross power. This means that even if there would have been no intrinsic imaginary power one would still measure non-zero contribution of the imaginary cross power spectrum. This conclusion makes sense intuitively. $Q_{\alpha\beta} = 0$ requires the distribution of Lyα and Lyβ absorptions to be symmetrical with respect to the inversion of the radial axis; a metal absorption at a small separation with a fixed sign will naturally break this symmetry.

Finally, we note that for this particular model of metal contamination, the contamination cancels perfectly for the cross-correlation coefficient defined as in Equation 2.15.
3 Data & Synthetic data

In this work we use BOSS quasars from the Data Release 9 (DR9; [1]) sample. The quasar target selection for the DR9 sample of BOSS observations is described in detail in [33] and we refer reader to that publication for the details.

We model continuum over the rest frame wavelength range of 978 Å to 1600 Å. This region is the same as in Ly$\alpha$ analysis of the paper Slosar et al. ([35]) but is extended to lower rest frame wavelengths to enclose the Ly$\beta$ forest. For the purpose of our analysis we define the Ly$\alpha$ forest to be 1041 − 1185 Å, which is similar to the range used by McDonald et al. ([27]) and more conservative than the range in [35]. The upper limit for the Ly$\alpha$ forest is thus roughly in the regime where proximity effects and Ly$\alpha$ emission line profile can be assumed to be small. For similar reasons, the lower limit is also kept a safe distance away from the Ly$\beta$ emission peak.

In similar spirit we define the Ly$\beta$ forest region as rest frame 978 − 1014 Å. This range is a bit more conservative than the Ly$\alpha$ range, since the Lyman emission peaks become narrower as one moves long the series (i.e. Ly$\beta$ emission peak is narrower than Ly$\alpha$ emission peak). The Ly$\beta$ forest range covers a much shorter path length than the Ly$\alpha$ region, which means inherently less signal. Also, we reiterate that while there is only Ly$\alpha$ absorption in the Ly$\alpha$ forest region defined in this paper, there are both Ly$\alpha$ and Ly$\beta$ absorptions in the Ly$\beta$ forest region. Of course, there is metal contamination throughout both forests.

3.1 Mock data

We tested our technique on the same mock data as used in [14, 35]. It is important to stress this mock data-set is not optimal for testing this analysis, since it is focused on the three-dimensional correlations. The small scale power is roughly correct, but only at an order-of-magnitude level. Since we are not aiming at precision cosmology, this should not be a major handicap for our study. If one demonstrates that we can measure the power spectrum without a major bias in these mock data-sets, we are also likely to be making reliable measurements in the true data.

To extend the mock data used in [35] to the Ly$\beta$ forest, we scaled the optical depth in the $\tau_\alpha$ field by $r_{\beta\alpha}$ (see Equation (1.2)) and translated it to an appropriate redshift. The Principal Component Analysis (PCA) continua do not extend to these low redshifts and so we artificially extend them with a constant value.

4 Application to mock data

We tested our analysis on the mock data as follows. First, we demonstrated that our quadratic estimator yields an unbiased result for a white noise input signal which perfectly cross-correlates $\alpha$ and $\beta$ fields. Next we applied our estimator to the mock data-set, assuming perfect knowledge of the continuum and mean absorption. These results were compared with the full analysis, in which we infer all the quantities from the data, as we must do with the real data. We present these results in Figures 2 and 3.

Figure 2 shows the inferred mean absorption from the mock data-set for both Ly$\alpha$ and Ly$\beta$, together with real measurements discussed in the next section. For this section, the relevant plot is Figure 3, which shows how fitting for the continuum fluctuations affects the measured power spectra. Small disagreements are consistent with the fact that the mock data-set misreports the noise-levels to mimic our real misunderstanding of the noise.
properties of spectrograph (see section 2.2 of [35]). We have also performed simpler tests for which we assumed the Ly$\alpha$ forest field to be perfectly white, fit the data with a single power spectrum bin and compared this with direct estimates using variances - this test convinced us that we do not have missing pre-factors in our estimator. However, we have not carefully tested redshift-interpolation and other more subtle aspects of the estimator.

These tests lead us to conclude that our data analysis will be able to reconstruct the measured power spectrum at the level of precision relevant for this exploratory work when applied to the real data.

5 Results

We applied our data reduction method to the data. Much of the analysis is common with [35] and we refer the reader to that publication for more details. In Figure 2 we plot $\bar{F}$ for Ly$\alpha$ and Ly$\beta$ forests in mock data and real data. The absolute normalization of each individual mean absorption is arbitrary (since it is degenerate with the mean continuum shape in the relevant forest regions). The error bars are underestimated, since they do not correctly take into account correlations between pixels. Nevertheless, the visual agreement between the results on the mock data and real data is quite good and, in fact, better than one would naively expect given that the small scale power is not appropriately reproduced in these mock data.

Next we discuss the covariance matrix of our measurements. In the top row of Figure 4 we show the covariance matrices derived from the optimal estimator and the data. The covariance matrix has the expected structure. Measurements of the Ly$\alpha$ power spectrum are effectively uncorrelated, with only weak anti-correlation between adjacent bins. Measurements of the Ly$\beta$ power spectra are similar, but the anti-correlations between adjacent bins are larger, since the available path length is smaller. Measurement of the cross-power spectra are also only weakly internally correlated, but they show significant correlations with both auto power spectra. The most interesting aspect is the covariance structure of the $Q_{\alpha\beta}$ with $P_{\alpha\beta}$, where bins at the same $k$ are uncorrelated, but are somewhat correlated with adjacent $k$-bins.

Measurements of the 1D quantities in the data are conveniently bootstrapped by assuming each quasar to be an independent measurement of this quantity (this should be an excellent approximation). We generated 3000 bootstrap samples of our dataset and calculated the corresponding bootstrap covariance matrix. When compared with the bootstrap derived covariance matrix, the estimator under-estimates the diagonal elements of the covariance matrix by approximately 10%. We correct for this error in subsequent use of the matrix by multiplying all element of the covariance matrix by 1.1. The correlation structure for this matrix is displayed in the bottom row of Figure 4. We see that compared to the estimator matrix, the structure is in general similar. One important difference is that the bootstrapping is selecting a constant-like contribution to variance in the auto-correlations. This feature likely arises due to our imperfect fitting of the quasar amplitude for small signal-to-noise quasars that modulates the power spectrum normalization.
Figure 5. Measured power spectrum components: Ly$\alpha$ power spectrum (red), Ly$\beta$ power spectrum (blue), real (green) and imaginary (magenta) part of the cross power spectrum. It can be clearly seen that both Ly$\alpha$ and real part of the cross power spectrum are detected with high significance while the imaginary part has lowest detection significance. Also apparent are oscillations in all four components. We compare our measurements with those by [27] and [30]. We have added the background contribution to both of those measurements.
So far, for example in mock-testing, we have completely neglected the effect of the finite spectrograph resolution and pixel size. Both effects smooth the observed fluctuations and thus dampen the power on small scales. To account for this effect properly, a correction has to be used in the estimator that convolves the power spectrum and the smoothing kernel for each $k$ bin of the power spectrum. Since for this work we were interested only in a rough estimate we proceed to make an approximate correction as follows. We estimate our beam correction as a mean of the correction kernel over pairs of pixels that contribute in the same $(k, z)$ bin. The beam correction we apply is thus given by a weighted average

$$B(k) = \frac{\sum_{i,j \in \text{pairs}} w_i w_j W(\lambda_i) W(\lambda_j)}{\sum_{i,j \in \text{pairs}} w_i w_j},$$

(5.1)

where the weights were given as inverse square variance for each pixel. The smoothing kernel is given by ([27])

$$W(k, \lambda_i) = \exp\left(-k^2 r_i^2\right) \text{sinc}\left(\frac{k p_i}{2}\right),$$

(5.2)

where $p_i$ is the pixel width for the pixel $i$ given by $\lambda_i$ and $r_i$ the resolution for the same pixel. The errors on the spectrograph resolution $r_i$ are estimated to be of order of 10% ([30]). This results in a substantial increase in the size of the error-bars in our measurements at high $k$.

In Figure 5 we compare our measurements and the measurements of the Ly$\alpha$ forest alone using 3000 SDSS quasars by [27]. For comparison we also add the measurements of the Ly$\alpha$ forest only by a recent study of the new BOSS release using 14000 BOSS quasars by [30]. In general, we find good agreement, except at the lowest redshift bin, where we measure excess power when compared to the other measurements. The most likely explanation for mismatch is poor noise modeling in our data, since it is known that the pipeline noise is not accurate [35].

Using the data plotted on Fig. 5 we estimated the significance with which we measure a non-zero imaginary part of the cross power spectrum $Q_{\alpha\beta}$. For this estimation we have only used modes with $k < 0.01$ km s$^{-1}$. Significance $s = \sqrt{\sum (Q_{\alpha\beta}/\sigma_{Q_{\alpha\beta}})^2}$ of $Q_{\alpha\beta}$ in each redshift bin was estimated to be $(z, s)$: (2.8, 8.24), (3.0, 7.23), (3.2, 4.97) and (3.4, 1.93). The total significance of measuring $Q_{\alpha\beta}$ different from zero was estimated to be 12.2$\sigma$. We caution reader that this significance corresponds to the contaminated cross power spectrum component given by Equation 2.29 and thus composes entangled information from both the intrinsic imaginary part of the power spectrum and metal contamination.

From Fig. 5 it is apparent that oscillations are imprinted on top of a smooth power spectrum. We propose that these oscillations are best described as being due to the presence of contaminating metal at small separation from the main absorption line ([27]).

In order to test this hypothesis, we fit our data as an instrumentally smooth power spectrum described by a 2nd order polynomial fit in log$(k)$. All four components ($P_{\alpha\alpha}$, $P_{\beta\beta}$, $P_{\alpha\beta}$, $Q_{\alpha\beta}$) were fit with independent smooth component at each redshifts. We convolved this model with a dominant metal contamination at fixed separation as described in the section 2.4. We assumed that contaminating oscillation strength is independent in each redshift bin, but that the oscillation frequencies ($v_\alpha$ and $v_\beta$) are fixed.

To get an appropriate initial parameters for the optimizer, we first used a simple model fitting only Ly$\alpha$ power spectrum with one contaminating metal. With this simpler model we explored a larger part of the phase-space and determined a rough estimate for Ly$\alpha$ frequency to lay around $\pm 2000$ km s$^{-1}$ (note that auto power spectra cannot determine the sign of the
Figure 6. Fits for power spectrum models with metal contaminants in Lyα and Lyβ forest. The model does not produce a good fit to the data, but the oscillation frequencies are measured very robustly.
contaminating velocity). We used the same simple model for Lyβ power spectrum only and again after exploring a large part of the phase-space for \( v_\beta \) found a rough estimate of around \( \pm 1800 \text{ km s}^{-1} \). We then proceeded to use those as starting points, with four possible sign permutations for a finer fitting with all available data, including cross-correlations. Only the presented sign combination converged.

The best-fit model resulting from this procedure can be found in Figure 6. This model did not produce a good fit to the data - in fact our best fit gives \( \chi^2 = 299.92 \) with 134 degrees of freedom (even after correcting for the 10% error-covariance underestimate). Not surprisingly, we have found that the two robustly measured quantities are the oscillation frequencies of the contaminating components, which are given by

\[
v_\alpha = 2269 \pm 19 \text{ km s}^{-1},
\]

\[
v_\beta = -1820 \pm 13 \text{ km s}^{-1}.
\]

Since we do not produce a good fit to the data, the error bars are likely underestimated. Nevertheless, we can identify the contaminants. The metal contaminant in Lyα forest (\( v_\alpha \)) is the SiIII line transition, absorbing at 1206.5Å, which is separated from Lyα by \( v_\alpha = 2271 \text{ km s}^{-1} \) confirming results by [27]. The contaminant in the Lyβ forest is identified with OVI that absorbs at 1031.9Å, corresponding to \( v_\beta = -1801 \text{ km s}^{-1} \).

We proceed by examining the cross-correlation coefficient defined in Equation 2.15. As mentioned in Section 2.4, under the simplified model of metal contamination, its effect cancels

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Figure 7. Measured cross correlation coefficient (2.15) from the data. Within the error bars, the coefficient is constant on large scales and is falling off towards smaller scales.
exactly in this quantity. Errors due to absolute noise power that affect the auto power spectra but not the cross power spectra will, in general, affect this quantity. The quantity $r_{αβ}(k)$ is plotted in Figure (7). The statistical error bars on this plot were derived by drawing samples of power spectra consistent with the measured data and the associated covariance matrix and examining the resulting scatter in $r$. Although the measurements are uncertain and error bars large, the general behavior follows the expectations. On large scale we see nearly unity cross-correlations that tends to decrease towards smaller scales.

6 Conclusion

In this paper we studied the possibility of measuring the Ly$\beta$ forest in spectra of quasars. The fact that the underlying density field evolves with redshift breaks the symmetry along the line of sight when measuring cross power spectrum which results in a cross-correlation function that is not symmetric with respect to changing the sign of the velocity difference. This yields an intrinsic non-zero imaginary component to the cross power spectrum. When considering the Ly$\beta$ in addition to Ly$\alpha$ forest, one therefore measures three new components. Including higher Lyman transitions will add new auto power spectra and in general two new cross-power spectra for any combination of absorbing lines. However, due to decreasing path-length of higher-order forests, it is not clear whether it is useful to venture beyond the Ly$\beta$ line.

Measurements of the Ly$\beta$ power spectrum and the Ly$\alpha$-Ly$\beta$ cross power spectra offer an improved way of estimating cosmological parameters over using the Ly$\alpha$ power spectrum alone, since we expect that many of the astrophysical nuisance parameters that are degenerate with the cosmologically interesting parameters can be measured semi-independently from the new quantities. This stems from the fact that the two transitions map the same intergalactic medium, but are sensitive to different density and temperature ranges. This presents an opportunity to better constrain IGM parameters of the flux-density transformation and thus break the degeneracies between IGM parameters (especially parameters of the equation of state) and cosmology parameters (e.g. scalar spectral index).

Measurements of the cross power spectra $P_{αβ}$ are independent of the choice of noise model. With future theoretical modeling, we should be able to predict the cross-correlation coefficient accurately and therefore the cross-power spectra will provide a convincing self-consistency check.

We have measured the quantities discussed above in the BOSS DR9 data. Our work is clearly not accurate at the level required for precision cosmology fits. In particular, effects of noise, spectrograph resolution and metal contamination (both in-forest like OVI, but also lower redshift metals that are uncorrelated with the signal of interest). Along with a better data analysis, the theory also needs to be further investigated using numerical simulations of the Ly$\beta$ forest. These are trivial to generate from the Ly$\alpha$ simulations by appropriate rescaling of the optical depth.

Nevertheless, we have measured power in all quantities discussed above with high significance. Our measurements confirm the standard picture describing the Ly$\alpha$ forest. The cross-correlation coefficient is close to unity on large scales as expected from qualitative arguments. We found oscillations in all the power spectra measured. Our fits indicate that these features are best explained by a combination of the SiIII contamination of the Ly$\alpha$ forest (known previously) and OVI contamination in the Ly$\beta$ forest (new to this work).
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