Background power subtraction in Lyα forest

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When measuring the one-dimensional power spectrum of the Lyα forest, it is common to measure the power spectrum in flux fluctuations redward of the Lyα emission of quasars and subtract this power from the measurements of the Lyα flux power spectrum. This removes excess power present in the Lyα forest which is believed to be dominated by metal absorption by the low-redshift metals uncorrelated with the neutral hydrogen absorbing in Lyα. In this brief report we note that, assuming the contaminants are additive in optical depth, the correction contains a second order term. We estimate the magnitude of this term for two currently published measurements of the 1D Lyα flux power spectrum and show that it is negligible for the current generation of measurements. However, future measurements will have to take this into account when errorbars improve by a factor of two or more.

I. INTRODUCTION

The Lyman-α forest measurements are becoming increasingly more accurate and to that end careful investigation of possible systematic effects is required. In this brief report we study the effect of background power fluctuations which contaminate the signal in the Lyα forest region.

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II. EFFECT OF CONTAMINANTS

For our analysis, we assume that observed flux in the relevant parts of quasar spectra is given by

\[ f^q(\lambda_i) = C^q(\lambda_p) \times \begin{cases} e^{-\tau_\alpha(z_i)-\tau_c(z_i)} & \text{in forest region} \\ e^{-\tau_c(z_i)} & \text{in background region} \end{cases} \]

(1)

where \( C^q(\lambda_p) \) is the continuum of the quasar (results in this paper do not depend on the modeling of this quantity) and \( \tau_\alpha \) and \( \tau_c \) are the optical depth associated with signal and contamination respectively. We write the absorptions as

\[ e^{-\tau_\alpha(z_i)} = \hat{F}_\alpha(z_i)(1 + \delta_\alpha(\lambda_i)) \]

(2)

\[ e^{-\tau_c(z_i)} = \hat{F}_c(z_i)(1 + \delta_c(\lambda_i)) \]

(3)

where \( \hat{F} \) is mean absorptions and \( \delta \) are the corresponding fluctuations for the two components. Here we have

\[ \text{Note that for a given observed wavelength } \lambda_\alpha, \text{ there are quasars at somewhat larger redshift } 1 + z \gg \lambda_\alpha/\lambda_\alpha \text{ for which the wavelength is subject to both Lyα and contaminant absorptions and other quasars at somewhat lower redshifts } 1 + z < \lambda_\alpha/\lambda_\alpha \text{ for which the same wavelength is absorbed only by the contaminant. Therefore one is subtracting statistically the same component, but observed in different quasars.} \]
written \( \delta_c \) as fluctuations due to low-redshift metals, but fluctuations due to continuum errors would have exactly the same form (i.e. be multiplicative). The forest region of the spectrum is the region of the forest blue-ward of Ly\( \alpha \) emission, typically between rest frame wavelengths of 1050\AA and 1185\AA. Different authors have defined different background regions where absorption by metals is measured but all regions share the same qualities of having as close as possible redward of Ly\( \alpha \) emission and have smooth continuum without large emission lines (see [2, 6, 7]).

Faced with the real quasar spectra, it is impossible to distinguish between various absorbers and the best one can hope to do is to model the quasar flux as [2, 6, 8]

\[
f^\alpha(\lambda_i) = C^\alpha(\lambda_i) \\
\times \begin{cases} 
F_T(z_i)(1 + \delta_T(\lambda_i)) & \text{in forest region} \\
F_c(z_i)(1 + \delta_c(\lambda_i)) & \text{in redward region}
\end{cases}, \tag{4}
\]

Inside the forest region the total fluctuation field can be written as

\[1 + \delta_T(\lambda) = (1 + \delta_a(\lambda))(1 + \delta_c(\lambda)). \tag{5}\]

We see that in addition to the usual linear relation used in previous works there is also a second order (quadratic) term in the total absorption flux fluctuation field in the forest

\[\delta_T(\lambda) = \delta_a(\lambda) + \delta_c(\lambda) + \delta_a(\lambda)\delta_c(\lambda). \quad \tag{6}\]

The correlation function of this quantity is given by

\[\langle \delta_T(\lambda)\delta_T(\lambda') \rangle = \xi_a(\lambda, \lambda') + \xi_c(\lambda, \lambda') + \xi_a(\lambda, \lambda')\xi_c(\lambda, \lambda'). \tag{7}\]

Here we have assumed that \( \delta_a \) and \( \delta_c \) are completely uncorrelated fields. This is justified by the fact that the metals doing the contaminant absorption are sitting in a gas that is \( > 1000h^{-1}\)Mpc away from hydrogen gas.

Fourier transforming, we find that power spectra are given by

\[P_T(k) = P_a(k) + P_c(k) + (P_a \ast P_c)(k), \tag{8}\]

where \( \ast \) stands for suitably normalized convolution.

On the quasar's red-side, there is no forest and therefore the measured power spectrum is simply \( P_c(k) \). The point of this short note is that when a corrected power spectrum is calculated, the second order correction does not cancel

\[P_{\text{std,correction}}(k) = P_T(k) - P_c(k) = P_a(k)(P_a \ast P_c)(k), \tag{9}\]

Therefore, to recover the sign power spectrum \( P_a \), it is not sufficient to simply subtract the contaminant power spectrum from the total power spectrum. In configuration space

\[\xi_a(x) = \frac{\xi_T(x) - \xi_c(x)}{1 + \xi_c(x)}, \tag{10}\]

which gives

\[P_a(k) = P_T(k) - P_c(k) - \Delta P(k), \tag{11}\]

where

\[\Delta P(k) = \int_{-\infty}^{\infty} dk' [P_T(k') - P_c(k')] W_K(k - k'), \tag{12}\]

and \( W_K \) is just the Fourier transform of a real space window function

\[W(x) = \frac{\xi_c(x)}{1 + \xi_c(x)}. \tag{13}\]

There are two interesting limits to these equations. First, if \( \xi_c(x) \) is small compared to other quantities, we see that \( W(k) \sim P_c(k) \), leading to

\[\Delta P(k) = (P_T \ast P_c)(k) \tag{14}\]

(in effect approximating \( P_a(k) \) with \( P_T(k) \) in Eq. 8). Second, when \( P_c(k) \) is white, we see that

\[\Delta P(k) = \frac{\sigma_T^2 \sigma_c^2}{2\pi}, \tag{15}\]

where \( \sigma_T \) and \( \sigma_c \) are the variances (i.e. zero lag correlators) of the \( \alpha \) and \( c \) fields. We see that in that limit, the correction is purely white too.

In order to properly account for this effect, one would need to take it into account in the quadratic estimator used to measure the power spectrum (and likely perform the measurements of background and forest power jointly). However, to get a rough estimate, one can take measurements of the power spectra, Fourier transform those measurements to the configuration space, perform correction and transform back. We do this for two published results in the next section.

### III. ESTIMATING THE SIZE OF THE EFFECT

To evaluate the correction from Eq. 12 we have used FFT algorithms to first compute the corresponding \( \xi_c \) and \( \xi_a \) and then to compute the inverse as given by Eq. 11. We did this for two published 1D power spectra [6, 7], which conveniently provided both the total power measured in the Ly\( \alpha \) forest region as well as background power measured redward of the Ly\( \alpha \) emission line. To deal with different binning schemes and finite coverage of \( k \)-space, we have first resampled the power spectra onto a finer \( k \)-space grid and given sufficient zero padding on both sides until results converged. We have also checked that the treating the power spectrum bins as either flat bandpower bins or linearly interpolating between bin centers made negligible difference.

In Figure 1 we plot the quantities \( P_T \), \( P_m \) and \( \Delta P \) on the same plot for three representative redshift bins. This plot shows that the correction is small, three orders
of magnitude smaller than the power spectrum and an order of magnitude smaller than the background power spectrum. The full lines show the analysis by [7] and the dashed lines show the first analysis by [6].

Note that due to small errorbars the correction is not as negligible as one might naively expect. In the Figure 2 we show the correction relative to the power spectra error estimates (both statistical and systematic). We see that for the current generation of power spectra measurements, the 2nd order correction is not yet important (around 10% of the current errors at redshift range \( z = 3 - 4 \)). The implied change in \( \chi^2 \) for previous works is \( \sim 1 \) for [6] (over 12 \( k \) bins and 11 redshift bins) and \( \sim 2 \) for [7] (at 35 \( k \)-bins and 12 redshift bins). This confirms that the size of the effect is probably negligible when compared to the current errorbars, but not by a large margin.

IV. CONCLUSIONS

In this brief report we have shown that multiplicative contaminations in the Lyman-\( \alpha \) forest, such as those arising from continuum fluctuations and low redshift metals cannot be simply subtracted by measuring them outside the forest region, but instead produce higher-order correction. This is typically small and indeed it does not matter for the current generation of the 1D power spectrum measurements.

The measurement of [7] has used approximately 14 thousands high signal-to-noise BOSS quasars, producing an effect of \( \Delta \chi^2 \sim 2 \). The full survey will contain ap-
proximately 160 thousand quasars and eBOSS and DESI experiments will likely increase the number of quasars to well over 600 thousand. This signal to noise is hence likely to increase by a factor of at least a few, bringing the expected size of the effect well into realm where correction will have to be applied.

Finally, we note that the correction mixes up small scales and large scales. While we can reliably say that small scale background power is likely coming from low-redshift metals, we cannot say the same for the large-scale power in the background region. Some of the power on those scales will be associated with the continuum fluctuations, but these are now estimated at a wrong part of the rest-frame spectrum. For simple power subtraction this does not matter, but since the second order correction mixes scales, this set a fundamental limitations on how well one can perform this correction. We do not deal with this question in this brief report, but undoubtedly new techniques will arrive that will attack these issues.

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