BAO Correlations at $z = 2.3$ with SDSS DR12 Lyman-alpha forests

Julian E. Bautista
Department of Physics and Astronomy, University of Utah,
115 S 1400 E, Salt Lake City, UT 84112, USA

1 Introduction

Sound waves propagating in the baryon-photon fluid prior to recombination created spherical overdense shells around primordial overdensities. These shells show up as a single peak in the two-point correlation function at a comoving separations $r_d \sim 150$ Mpc, or, equivalently in Fourier space, as oscillation in the matter power-spectrum. This particular separation, known as sound horizon or baryon acoustic oscillations (BAO) scale, has been used as a cosmological statistical standard ruler [1], since its size increases, after recombination, mainly under the effect of the expansion of the Universe.

Observed in the cosmic microwave background (CMB) [2] at redshift $z \sim 1100$, the BAO scale was also measured at percent level precision in galaxy two-point functions at $z < 1.0$ (cite many galaxy BAO papers). Combined, high and lower redshift measurements provide the best constraints on dark energy and curvature, complementary to supernovae Hubble diagram[3].

In the last five years, the Baryon Oscillation Spectroscopic Survey (BOSS [4]) opened a new window for BAO measurements at intermediate redshifts using the two-point correlation function of the flux in the Lyα forest. Using the Sloan Digital Sky Survey 2.5-meter telescope, BOSS observed spectra of more than 190 000 quasars at $z > 2$ and obtained an unique 2.5% measurement of BAO at $z = 2.3$ [5,6].

The paper is organized as follows. In section 2, the main steps of the BAO Lyα analysis are presented. Then, I summarize the previous measurement of BAO using Data Release 11[7] (section 3) and I introduce the main improvements on the data analysis that is currently in progress on the full BOSS data-sample (section 4).

2 Basis of Lyα forest clustering

The Lyα forest is the region of the rest-frame quasar spectrum showing numerous absorption lines due to absorption of quasar light by low density neutral hydrogen in intergalactic medium (IGM), over the quasar line-of-sight.

The fraction F of quasar flux, at a given observed frame wavelength λ, that reaches the telescope depends on the amount of neutral hydrogen at $z = \lambda/\lambda_{Ly\alpha} - 1$. Therefore, fluctuations in the transmitted flux fraction around the mean, defined as $\delta_F = F/\bar{F} - 1$, are tracers of fluctuations of the underlying dark matter field. In other words, denser regions yield more absorption, or less transmission F. Several cosmological hydrodynamical simulations[8,9] have shown that on sufficiently large scales (above tens of Mpc comoving) the two-point function of δ_F is *linearly* related to the matter two-point function[a].

Past and current analysis of the three-dimensional clustering of the Lyα forest share some common steps:

- Obtaining correct quasar redshifts: visual inspection[10] of all quasar targets provided z estimates and flagged features such as Broad Absorption Systems (BALs) and Damped Lyα systems (DLAs);
- Estimating flux fluctuations over the forests: two automated methods were developed and give consistent BAO results. The main idea is to fit a fixed shape in rest-frame over all forests, tilting them with a linear function to take into account flux calibration errors. The first method assumes Gaussianity of the F field, while the second actually estimates the unabsorbed flux level.
- Estimating the two point function of fluctuations: we compute the flux auto-correlation function, but also use quasars as tracers by computing the quasar-flux cross-correlation. The covariance matrix of our measurements are estimated both using sub-samples of the data or explicitly computing the 4-point functions. Both methods are consistent with each other.
- Fitting for the BAO scale: we use the `baofit`[b] package[11] to find the best-fit two-point function models, scaling the radial and angular BAO peak position by two parameters,

$$\alpha_\parallel = \frac{D_H(\bar{z})/r_d}{[D_H(\bar{z})/r_d]_{\rm fid}} \qquad \text{and} \qquad \alpha_\perp = \frac{D_A(\bar{z})/r_d}{[D_A(\bar{z})/r_d]_{\rm fid}}, \tag{1}$$

  where D_H and D_A are respectively Hubble and angular diameter distances at effective redshift $\bar{z} \sim 2.3$, r_d is the comoving size of the sound horizon and the subscript "fid" denotes the value at the assumed fiducial cosmology (used to translate redshifts into comoving separations). Nuisance parameters are added to the models to capture any broadband distortions of the correlation function.

Mock catalogs were an essential tool in order to access biases eventually introduced by our analysis procedure, and to test and quantify other sources of systematics. One hundred realizations of DR11 were generated, simulating a realistic correlation function and including instrumental noise and flux calibration errors[12].

3 Current status of Lyα forest BAO measurements

The latest measurements of BAO correlations in the Lyα forest auto-correlation [5] and quasar-Lyα cross-correlation [6] using DR11 data yield the constraints shown in Figure 1. The best-fit values are:

$$\text{Auto}: \qquad D_H(2.3)/r_d = 9.18 \pm 0.28 \qquad D_A(2.3)/r_d = 11.28 \pm 0.65 \tag{2}$$

$$\text{Cross}: \qquad D_H(2.3)/r_d = 9.07 \pm 0.30 \qquad D_A(2.3)/r_d = 10.78 \pm 0.42 \tag{3}$$

If we assume that auto and cross-correlation are independent, these results give a 2.5σ tension with Planck 2013 + WP + SPT + ACT predictions. This tension was reduced to 2.4σ using Planck 2015[2] "TT+lowP+lensing" flat model.

Systematic contributions to errors were computed in these analyses but no evident source of contamination was found at this precision level. Those tests include:

[a] There are assumption in the simulations, such as constant ionizing background, but current observations are not sensitive yet to these second-order effects

[b] `http://darkmatter.ps.uci.edu/baofit`

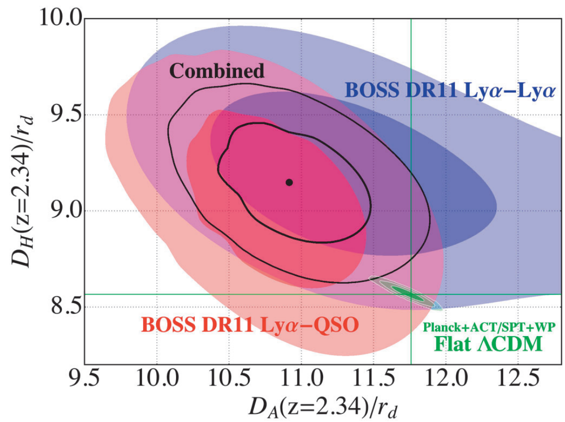

Figure 1 – Constraints on angular and radial BAO, $(D_A/r_d, D_H/r_d)$. Contours show 68.3% ($\Delta\chi^2 = 2.3$) and 95.5% ($\Delta\chi^2 = 6.2$) contours from the auto-correlation (blue), the quasar-Lyα forest cross-correlation (red), and the combined constraints assuming no correlation (black). The green contours are CMB constraints calculated using the Planck+WP+SPT+ACT chains assuming a flat ΛCDM cosmology.

- Varying the functional form of the broadband model, increasing the number of free parameters.
- Simulating the presence of metals in the forests using mock catalogs based on stacked forests[13]. In particular the Si II(1260)-Lyα cross-correlation creates a bump at $r_\parallel \sim 110$ Mpc$/h$ and $r_\perp = 0$ that could bias the BAO measurement. Using 10 mocks, we found no evidence for shifts caused by this metal transition. In section 4, we describe an improvement to this test.
- Computing the contribution of flux calibration residuals that created bumps in flux at observer-frame wavelengths corresponding to Balmer transitions. One pair of these transitions fall over the BAO peak when translated into comoving separations at $z = 2.3$. We found that this signal is negligible compared to the total signal.

4 Towards the final analysis of BOSS DR12 Lyα forest sample

The final BOSS sample, released as part of DR12, contains 15% more quasars than DR11. In terms of pairs of forest pixels, it corresponds to a 18% gain in statistical power. As it is still work in progress, I do not present any cosmological preliminary results in this paper. Instead, I overview the main improvements in the analysis and in the quantification of systematic errors. The bottom line is that no systematic error was found to be significant at this statistical precision level.

Improved spectral reconstruction When extracting 1D spectra from 2D CCD images, the DR12 optimal extraction algorithm would create a bias in the flux counts due to weighting schemes that use the data itself. We re-reduced the data changing the weighting scheme, while correctly propagating errors. This procedure reduced significantly the contamination of sky residuals in quasar spectra.

Spectral throughput corrections To optimize the throughput in the Lyα forest region of spectra ($\lambda \sim 4000$ Å), quasar optical fibers where placed differently in the focal plane than the standard stars used to calibrate flux. Therefore, the DR12 quasar flux calibration is not correct. Corrections based on these focal plane shifts were computed[14] and applied all quasar spectra[c].

Marginalization over metal correlations in the BAO fitting Using different models of metal contamination in mock spectra, we studied in more detail the impact of the cross-correlation Lyα-metal on the inference of BAO. As mentioned in section 3, the Si II(1260)-Lyα cross-correlation creates a worrying excess of correlation over the BAO peak. In this new analysis, we marginalize over the amplitude of the metal-Lyα and metal-metal cross-correlations in the flux correlation function.

We test this marginalization using noise-free mocks with strong metal absorption (stronger than seen in data). We see a 2% bias in $\alpha_{\parallel}$ and $\alpha_{\perp}$ on these mocks because of metal contamination. When using templates to marginalize over these cross-correlations, the bias on α is successfully corrected on mocks.

Improved modeling of continuum fitting distortions Our methods to compute flux fluctuations use information on the forest itselt, suppressing power on scales comparable to the size of the forest. This power suppression is referred to as distortion by continuum fitting. These distortions are marginalized over in previous analyses through the use of smooth functions of separation and angle with respect to the line of sight while fitting for BAO. The new analysis attempt to model this power suppression differently by transforming the fluctuation field such that the distorted correlation function can be computed theoretically using the distribution of pixels.

Null tests We tested any source of non-physical correlations by building sets of fake forests, cross-correlating them with true forests. Fake forests were built using the quasar flux redwards of the Lyα emission line (where no hydrogen absorption is expected) or galaxy spectral residuals (galaxy spectra with its best-fit model subtracted). A significant non-zero signal is found when cross-correlating pairs of spectra in the same observing plate and same spectrograph. For pairs in different observing plates/spectrographs the correlation is compatible with zero. This non-zero signal is well modeled by correlations induced by noise in the sky modeling and flux calibration, i.e., by the data reduction process itself. While these undesired correlations distort the measured correlation function, these signals do not bias the inference of the BAO peak position, at this precision level.

Other sources of contamination, such as light cross-talk among neighboring optical fibers or interstellar medium absorption, show no impact on the derived cosmological parameters.

5 Conclusion

In this paper, I summarized the current status of the measurement of baryon acoustic oscillations using the complete sample of Lyα forests from BOSS.

Using DR11 data, the combined measurement of BAO using the flux-flux correlation function and the quasar-flux cross-correlation yields a 2.5% precision inference of the Hubble expansion rate at $z = 2.3$. The 2.5σ tension with the CMB predictions inspired careful studies of systematics on the Lyα BAO results.

The currently in-progress analysis of the full BOSS sample, released in DR12, shows confident quantification of many sources of spurious correlations that could in principle bias the BAO measurement. The uncertain amount of contamination by metal-Lyαcross-correlations is now marginalized over when BAO fitting, making the estimates of cosmological parameters more robust. The final results are expected to be published in some months from now.

[c]These corrections are publicly available at `http://darkmatter.ps.uci.edu/tpcorr/`

Acknowledgments

I would like to thank the organizers for the invitation for this wonderful and enriching conference.

References

1. David H. Weinberg, Michael J. Mortonson, Daniel J. Eisenstein, et al. Observational Probes of Cosmic Acceleration. *arXiv:1201.2434*, January 2012.
2. Planck Collaboration. Planck 2015 results. XIII. Cosmological parameters. *arXiv:1502.01589 [astro-ph]*, February 2015. arXiv: 1502.01589.
3. M. Betoule, R. Kessler, J. Guy, et al. Improved cosmological constraints from a joint analysis of the SDSS-II and SNLS supernova samples. *Astronomy and Astrophysics*, 568:22, August 2014.
4. Kyle S. Dawson, David J. Schlegel, Christopher P. Ahn, et al. The Baryon Oscillation Spectroscopic Survey of SDSS-III. *The Astronomical Journal*, 145:10, January 2013.
5. Timothée Delubac, Julian E. Bautista, Nicolás G. Busca, et al. Baryon acoustic oscillations in the Ly-alpha forest of BOSS DR11 quasars. *Astronomy and Astrophysics*, 574:A59, February 2015.
6. Andreu Font-Ribera, David Kirkby, Nicolas Busca, et al. Quasar-Lyman alpha forest cross-correlation from BOSS DR11: Baryon Acoustic Oscillations. *Journal of Cosmology and Astro-Particle Physics*, 05:027, May 2014.
7. Shadab Alam, Franco D. Albareti, Carlos Allende Prieto, et al. The Eleventh and Twelfth Data Releases of the Sloan Digital Sky Survey: Final Data from SDSS-III. *arXiv:1501.00963 [astro-ph]*, January 2015. arXiv: 1501.00963.
8. Jordi Miralda-Escudé, Renyue Cen, Jeremiah P. Ostriker, and Michael Rauch. The Ly alpha Forest from Gravitational Collapse in the Cold Dark Matter + Lambda Model. *The Astrophysical Journal*, 471:582, November 1996.
9. Patrick McDonald. Toward a Measurement of the Cosmological Geometry at z ˜ 2: Predicting Ly-alpha Forest Correlation in Three Dimensions and the Potential of Future Data Sets. *The Astrophysical Journal*, 585:34–51, March 2003.
10. Isabelle Pâris, Patrick Petitjean, Éric Aubourg, et al. The Sloan Digital Sky Survey quasar catalog: tenth data release. *Astronomy and Astrophysics*, 563:A54, March 2014.
11. David Kirkby, Daniel Margala, Anže Slosar, et al. Fitting methods for baryon acoustic oscillations in the Lyman-alpha forest fluctuations in BOSS data release 9. *Journal of Cosmology and Astro-Particle Physics*, 03:024, March 2013.
12. Julian E. Bautista, Stephen Bailey, Andreu Font-Ribera, et al. Mock Quasar-Lyman-alpha forest data-sets for the SDSS-III Baryon Oscillation Spectroscopic Survey. *Journal of Cosmology and Astro-Particle Physics*, 05:060, May 2015.
13. Matthew M. Pieri, Michael J. Mortonson, Stephan Frank, et al. Probing the circumgalactic medium at high-redshift using composite BOSS spectra of strong Lyman alpha forest absorbers. *Monthly Notices of the Royal Astronomical Society*, 441:1718–1740, June 2014.
14. Daniel Margala, David Kirkby, Kyle Dawson, et al. Improved Spectrophotometric Calibration of the SDSS-III BOSS Quasar Sample. *arXiv:1506.04790 [astro-ph]*, June 2015. arXiv: 1506.04790.


RENCONTRES DE MORIOND
50


La Thuile