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The Lyman α forest and *WMAP* year three

Matteo Viel,[1,2]★ Martin G. Haehnelt[1] and Antony Lewis[1]

[1] *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
[2] *INAF – Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, I-34131 Trieste, Italy*

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ABSTRACT

A combined analysis of cosmic microwave background (CMB) and Lyman α forest data can constrain the matter power spectrum from small scales of about $1\,h^{-1}$ Mpc all the way to the horizon scale. The long lever arm and complementarity provided by such an analysis have previously led to a significant tightening of the constraints on the shape and the amplitude of the power spectrum of primordial density fluctuations. We present here a combined analysis of the *WMAP* three-year results with Lyman α forest data. The amplitude of the matter power spectrum σ_8 and the spectral index n_s inferred from the joint analysis of high- and low-resolution Lyman α forest data as analysed by Viel & Haehnelt are consistent with the new *WMAP* results to within 1σ. The joint analysis with the mainly low-resolution data as analysed by McDonald et al. suggests a value of σ_8 that is $\sim 2\sigma$ higher than that inferred from the *WMAP* three-year data alone. The joint analysis of the three-year *WMAP* and the Lyman α forest data also does not favour a running of the spectral index. The best-fitting values for a combined analysis of the three-year *WMAP* data, other CMB data, 2-degree Field (2dF) data and the Lyman α forest data are $(\sigma_8, n_s) = (0.78 \pm 0.03, 0.96 \pm 0.01)$.

Key words: cosmic microwave background – cosmological parameters – cosmology: observations – cosmology: theory – quasars: absorption lines.

1 INTRODUCTION

Measurements of the matter power spectrum from Lyman α forest data extend to smaller scales and probe a redshift range complementary to estimates of the matter power spectrum from the cosmic microwave background (CMB), galaxy surveys or weak gravitational lensing observations (e.g. Croft et al. 1998, 2002, hereafter C02; Gnedin & Hui 1998; McDonald et al. 2000; Hui et al. 2001; McDonald 2003; Viel et al. 2003; Meiksin & White 2004; Viel, Haehnelt & Springel 2004b, hereafter VHS).

The combined analysis of Lyman α forest data with the first year of *Wilkinson Microwave Anisotropy Probe* (*WMAP*) data (Spergel et al. 2003, hereafter *WMAP*1) suggested that the fluctuation amplitude of the matter power spectrum on small scales was rather high ($\sigma_8 \sim 0.9$) and that there was no significant deviation of the spectral index of primordial density fluctuations from a Harrison–Zeldovich spectrum ($n_s = 1$). There was also no evidence for a (large) running of the spectral index, a non-zero neutrino mass or a deviation from a cold dark matter spectrum at small scales (VHS; Viel, Weller & Haehnelt 2004c; McDonald et al. 2005a, hereafter M05; Viel et al. 2005; Seljak et al. 2005; Beltran et al. 2005; Lidz et al. 2006; Abazajian 2006).

Viel et al. (2004c) found $\sigma_8 = 0.94 \pm 0.08$, $n = 0.99 \pm 0.03$ (1σ) and no evidence for a (large) running of the spectral index in a combined analysis of a large sample of high-resolution quasar (QSO) absorption spectra at $z \sim 2.5$ (C02; Kim et al. 2004) and the *WMAP*1 data. Similar results, with somewhat smaller errors ($\sigma_8 = 0.90 \pm 0.03$, $n_s = 0.98 \pm 0.02$), have been subsequently obtained by the Sloan Digital Sky Survey (SDSS) collaboration in a combined analysis of the *WMAP*1 and other CMB data, SDSS galaxy survey data and SDSS Lyman α forest data (Seljak et al. 2005). The Lyman α forest data analysed by M05 and Seljak et al. (2005) consists mainly of low-resolution low signal-to-noise ratio SDSS spectra with a wide redshift coverage ($2 < z < 4$) to which they added a small sample of eight high-resolution spectra (McDonald et al. 2000). The flux power spectrum was modelled using dark matter simulations, which took into account hydrodynamical effects in an approximate way and were calibrated with a few hydrodynamical simulations. Viel & Haehnelt (2006) found $\sigma_8 = 0.91 \pm 0.07$, $n_s = 0.95 \pm 0.04$ for the SDSS Lyman α forest data alone using a suite of state-of-the-art full hydrodynamical simulations. Further studies of Lyman α forest data by Desjacques & Nusser (2005), Jena et al. (2005) and Zaroubi et al. (2006) also came to similar conclusions.

The *WMAP*3 data alone argue now for significant deviation from a Harrison–Zeldovich spectrum, $n_s = 0.95 \pm 0.02$, and a smaller value for the fluctuation amplitude on small scales, $\sigma_8 = 0.74 \pm 0.06$ (Spergel et al. 2006). The *WMAP* team chose not to update their

★E-mail: viel@ast.cam.ac.uk

combined analysis of CMB and Lyman α forest in their *WMAP*3 data release. In this Letter we will present such a joint analysis.

2 THE DATA SETS

2.1 *WMAP*

The *WMAP*[1] satellite has mapped the entire sky in five frequency bands between 23 and 94 GHz with polarization-sensitive radiometers. The temperature power spectrum has been measured over a large range of scales ($l < 1000$) to an unprecedented accuracy (Hinshaw et al. 2006). We will use the temperature and polarization (Page et al. 2006) power spectra and maps as used by the *WMAP* likelihood codes (Verde et al. 2003; Spergel et al. 2006), as implemented in the code COSMOMC[2] (Lewis & Bridle 2002).

2.2 Lyman α forest data sets

We will investigate two different Lyman α forest data sets: the sample of high-resolution QSO absorption spectra used by VHS and Viel et al. (2004c), consisting of the Large Uves Quasar Absorption Spectra (LUQAS) sample (27 high-resolution QSOs) (Kim et al. 2004) and the (reanalysed) sample of C02 (30 high-resolution and 23 low-resolution spectra); and the SDSS Lyman α forest data as presented by McDonald et al. (2006). The SDSS Lyman α forest data set consists of 3035 QSO spectra with low resolution ($R \sim 2000$) and low signal-to-noise ratio ($\sim$10 per pixel) spanning a wide range of redshifts ($z = 2.2$–4.2), while the LUQAS and the C02 samples contain mainly high-resolution ($R \sim 45\,000$), high signal-to-noise ratio (>50 per pixel) QSO spectra with median redshifts of $z = 2.125$ and 2.72, respectively. Modelling the flux power spectrum of the Lyman α forest accurately for given cosmological parameters is not as straightforward as modelling the CMB power spectra, and accurate numerical simulations are required. M05 modelled the flux power spectrum using a large number of hydro-particle mesh (HPM) simulations (Gnedin & Hui 1998; Viel, Haehnelt & Springel 2006), calibrated with a few full hydrodynamical simulations. VHS improved instead the effective bias method developed by C02 [see Gnedin & Hamilton (2002) and Zaldarriaga, Scoccimarro & Hui (2003) for a critical assessment of the errors involved], by using a grid of full hydrodynamical simulations run with the Tree–smoothed particle hydrodynamics (Tree–SPH) code GADGET-2 (Springel, Yoshida & White 2001; Springel 2005) to infer the linear matter power spectrum. Viel & Haehnelt (2006) used a Taylor expansion of the flux power spectrum around best-fitting values based on full hydrodynamical simulations to model the dependence of the flux power on cosmological and astrophysical parameters in their independent analysis of the SDSS Lyman α forest data.

3 RESULTS

3.1 Incorporating the Lyman α data into COSMOMC

The linear dark matter power spectra inferred from the two Lyman α forest data sets have been incorporated into the new publicly available version of COSMOMC. The VHS power spectrum consists of estimates of the linear dark matter power spectrum at nine values of the wavenumber k at $z = 2.125$ and nine values at $z = 2.72$, in the range $0.003 < k\ (\mathrm{s\,km^{-1}}) < 0.03$. The estimate of the uncertainty of the overall amplitude of the matter power spectrum is 29 per cent. This estimate takes into account possible systematic and statistical errors (see the relevant tables of VHS for a detailed discussion). M05 provided a measurement of slope and amplitude of the matter power spectrum at $z = 3$ at a wavenumber $k = 0.009\ \mathrm{s\,km^{-1}}$ with an estimate of the 1σ error of the amplitude of $\sim$14 per cent. M05 have also made available a table that gives the minimum χ^2 for a given cosmological model as a function of the amplitude and slope after marginalization over a wide range of cosmological and 'nuisance' parameters. The nuisance parameters characterize a range of astrophysical and noise-related systematic uncertainties. We have furthermore implemented the modelling of the SDSS flux power spectrum with the method of Viel & Haehnelt (2006) based on a Taylor expansion of the flux power spectrum around a best-fitting model.

3.2 Constraints on σ_8 and n_s

To make contact with previous analyses, we show the marginalized 1σ and 2σ likelihoods in the n_s–σ_8 plane in Fig. 1. The coloured contours in the left-hand panel show the constraints for the VHS sample (light cyan) and the SDSS sample (dark blue) with the likelihood estimates provided by M05 and the constraints for the *WMAP*1 data (light green). In all cases we have assumed the Universe to be flat, no contribution from tensor perturbations, a pure cosmological constant ($w = -1$) and neutrinos with negligible mass. For the analysis of the *WMAP*1 data we have assumed a prior on the Thomson optical depth $0 < \tau < 0.3$.

The dark solid (SDSS) and light dashed (VHS) contours show the joint constraints for the Lyman α forest and *WMAP*1 data. As pointed out by Viel & Haehnelt (2006), there is remarkable agreement between the two joint analyses with the high-resolution absorption spectra as analysed by VHS and Viel et al. (2004c) and the larger sample of low-resolution SDSS spectra as analysed by M05 and Seljak et al. (2005). The Lyman α forest data break some of the degeneracies of the *WMAP*1 data which are responsible for the elongated shape of the error contours. The joint analysis tightens the constraints in the n_s–σ_8 plane by a factor of $\sim$2 (VHS) and $\sim$4 (M05), compared with the constraints from the *WMAP*1 data alone, but offers less help in improving the constraints on n_s. As discussed above and summarized in Table 1, in the combined analysis with the *WMAP*1 data the best-fitting value of the spectral index is not significantly different from $n_s = 1$ and $\sigma_8 \sim 0.9$. The significantly smaller error bars of the SDSS data set are due to the much larger sample: the wider range of redshifts covered is responsible for breaking some of the degeneracies intrinsic to the Lyman α forest data (M05).

In the right-hand panel of Fig. 1 we show how the situation has changed with the *WMAP*3 data. As discussed in Spergel et al. (2006) and Page et al. (2006), the contours for the *WMAP*3 data have shrunk by a factor of $\sim$3 compared with those of *WMAP*1 and lie at the bottom part of the region allowed by the latter. This is mainly due to the improved measurement of the optical depth from the large-scale polarization (Page et al. 2006; Lewis 2006).

In the case of the high-resolution VHS sample the errors are too large to tighten the *WMAP*3 constraints significantly. The joint analysis of *WMAP*3 with the SDSS Lyman α forest data places now even tighter constraints at the bottom end of the range preferred by the SDSS Lyman α forest data alone, about 2σ above the best-fitting value from the *WMAP*3 only data: $\sigma_8 = 0.86 \pm 0.03$ (see also Lewis 2006). The discrepancy is larger than may be naively inferred from the overlap of the Lyman α only and *WMAP*3 only analyses

[1] http://lambda.gsfc.nasa.gov

[2] http://cosmologist.info/cosmomc/

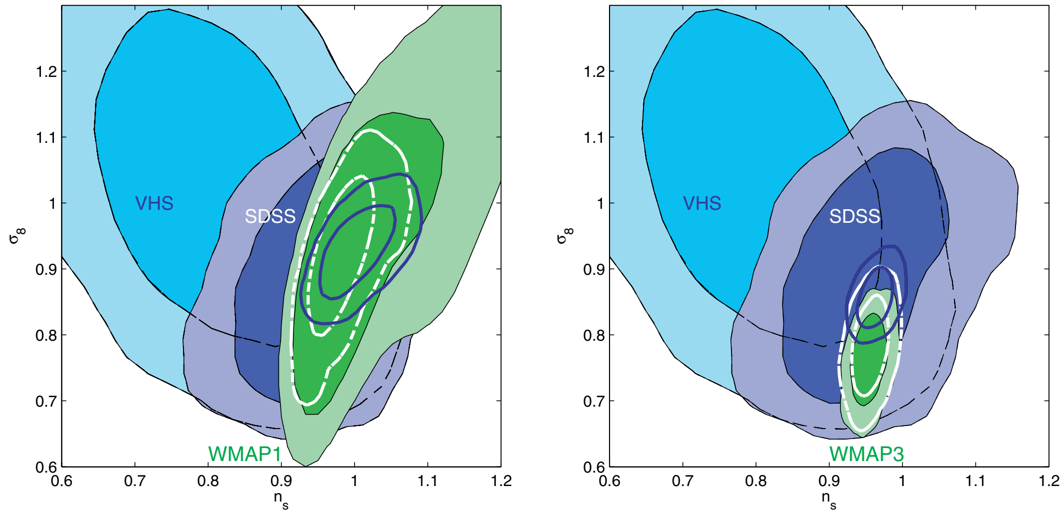

Figure 1. 1σ and 2σ likelihoods for σ_8 and n_s marginalized over all other parameters. Left-hand panel: constraints are for *WMAP*1 only (green), the LUQAS + Croft data sets as analysed by VHS (cyan) and the SDSS Lyman α forest data of M05 (blue). The thick dashed white empty contours refer to *WMAP*1 + VHS, while the solid blue contours are for *WMAP*1 + SDSS. Right-hand panel: as in the left-hand panel but for the *WMAP*3 data set.

Table 1. Summary of the constraints on σ_8 and n_s for the VHS and SDSS M05 samples. SDSS-d refers to the analysis of SDSS data by Viel & Haehnelt (2006). The quoted errors are the 68 per cent confidence limits.

	*WMAP*1	*WMAP*1+VHS	*WMAP*1+SDSS	*WMAP*3	*WMAP*3+VHS	*WMAP*3+SDSS	*WMAP*3+SDSS-d
σ_8	0.90 ± 0.10	0.94 ± 0.08	0.93 ± 0.04	0.76 ± 0.05	0.78 ± 0.05	0.86 ± 0.03	0.80 ± 0.04
n_s	0.99 ± 0.04	0.99 ± 0.03	0.99 ± 0.03	0.96 ± 0.02	0.96 ± 0.02	0.96 ± 0.02	0.96 ± 0.01

because the data sets prefer different values for some of the other parameters, in particular Ω_m. The best-fitting value for Ω_m ($\sim$0.3) is also $\sim 2\sigma$ higher for the combined analysis than for the *WMAP*3 data alone. The SDSS Lyman α forest data as analysed by M05 and the new *WMAP* results appear to be marginally consistent. Possible explanations for the (small) discrepancy, if there exists one, may be somewhat too optimistic errors for one or both of the data sets. As discussed in Page et al. (2006), the polarization measurements of the CMB are very difficult, mainly because of foreground polarization. Moreover, modelling the Lyman α forest data also has a range of not yet fully understood systematic uncertainties.

As discussed extensively by McDonald et al. (2005b) and Viel & Haehnelt (2006), the major systematic uncertainties are the still not very accurately known thermal state of the intergalactic medium, the determination of the effective optical depth, the modelling of the effect of strong absorption-line systems (Viel et al. 2004a) and ultraviolet fluctuations, and the remaining deficiencies in our ability to predict the flux power spectrum accurately for a large parameter space. To investigate the last issue issue further we compare in the left-hand panel of Fig. 2 the analysis of the SDSS data by M05 with that by Viel & Haehnelt (2006) which is based on a Taylor expansion of the flux power spectrum around a best-fitting model (labelled as SDSS-d in Fig. 2). The analysis of Viel & Haehnelt (2006) uses more accurate full hydro-simulations instead of the approximate simulations of M05 at the expense of a much less complete sampling of parameter space, especially far from the best-fitting values, where the errors are possibly underestimated. Note that here, for both the forest data and the joint analysis, we assumed a *Hubble Space Telescope* (*HST*) prior for the Hubble constant (Freedman et al. 2001) that significantly shrinks the error contours for the Lyman α forest data compared with that of Fig. 1. As discussed by Viel & Haehnelt (2006), there is remarkable agreement between the two analyses [note that the analysis of Viel & Haehnelt (2006) does not use the last three redshift bins, nor high-resolution QSOs, compared with that of M05]. In the right-hand panel of Fig. 2 we show the constraints for the joint analysis with the *WMAP*3 data. The SDSS Lyman α forest data as analysed by Viel & Haehnelt (2006) combined with *WMAP*3 give a smaller best-fitting value of $\sigma_8 = 0.80 \pm 0.04$ which is in agreement with that from the *WMAP*3 data alone to within 1σ. The joint analysis of Lyman α forest data and the new *WMAP* data including a possible running of the spectral index gives $n_{\rm run} = -0.002 \pm 0.015$ at $k = 0.002$ Mpc^{-1}, also in agreement with the estimate by Spergel et al. (2006).

We have also performed an extended combined analysis that includes the further CMB experiments Arcminute Cosmology Bolometer Array Receiver (ACBAR; Kuo et al. 2004), CBI (Readhead et al. 2004) and VSA (Dickinson et al. 2004), the 2-degree Field (2dF) galaxy power spectrum (Percival et al. 2001), and the VHS and SDSS-d Lyman α forest data. In this case we get (σ_8, n_s) = (0.78 ± 0.03, 0.96 ± 0.01). We note that these constraints are in agreement (although with smaller error bars) with those obtained by Sanchez et al. (2006) using WMAP1, other CMB experiments and the 2dF galaxy power spectrum. Further results are listed in Table 2.

4 CONCLUSIONS

We have performed a combined analysis of the *WMAP* three-year results with high- and low-resolution Lyman α forest data in order

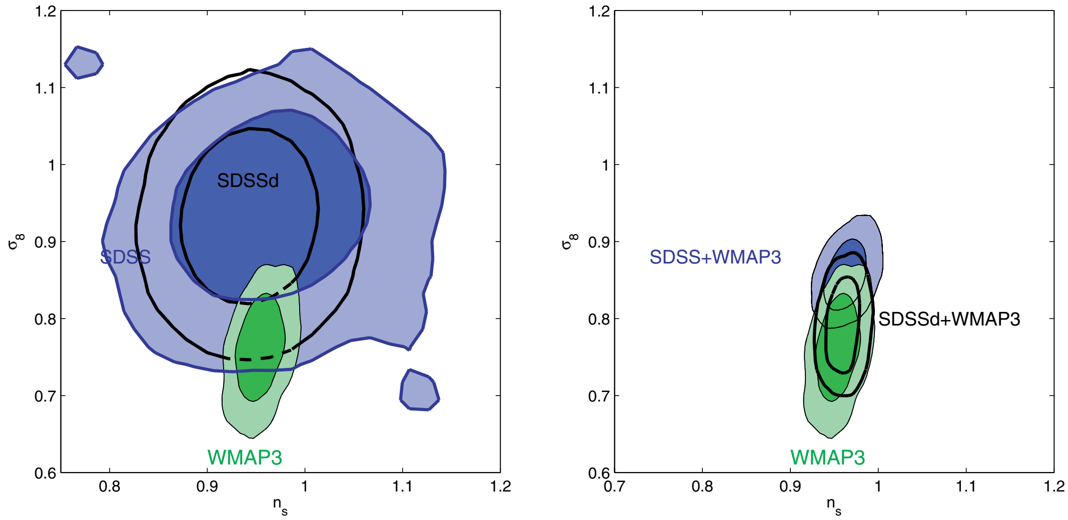

Figure 2. 1σ and 2σ likelihoods for σ_8 and n_s marginalized over all other parameters. Left-hand panel: the blue contours show the constraints for SDSS only as analysed by M05 with an *HST* prior 72 ± 8 km s^{-1} Mpc^{-1} (blue). The empty solid contours are for the SDSS data set as analysed by (Viel & Haehnelt 2006, SDSS-d). The *WMAP*3 results are shown in green. Right-hand panel: the combined analysis with *WMAP*3 using the same colour/line coding as in the left-hand panel.

Table 2. The marginalized constraints on cosmological parameters from *WMAP*3 and other data sets. VHS refers to the LUQAS + Croft sample as analysed by VHS; SDSS refers to the measurement by M05; EXT refers to smaller scale CMB data sets: ACBAR (Kuo et al. 2004), CBI (Readhead et al. 2004), VSA (Dickinson et al. 2004) and the 2dF Galaxy Survey (Percival et al. 2001). SDSS-d refers to the SDSS analysis by Viel & Haehnelt (2006).

	*WMAP*3	*WMAP*3+VHS	*WMAP*3+SDSS	*WMAP*3+SDSS-d	*WMAP*3+EXT+SDSS-d	*WMAP*3+SDSS-d(runn.)
$\Omega_c h^2$	0.106 ± 0.007	0.109 ± 0.008	0.120 ± 0.006	0.110 ± 0.006	0.109 ± 0.006	0.112 ± 0.007
$10^2 \Omega_b h^2$	2.222 ± 0.069	2.237 ± 0.072	2.277 ± 0.065	2.226 ± 0.071	2.224 ± 0.066	2.221 ± 0.094
Ω_m	0.242 ± 0.032	0.257 ± 0.037	0.304 ± 0.031	0.258 ± 0.029	0.253 ± 0.028	0.269 ± 0.036
h	0.729 ± 0.029	0.719 ± 0.031	0.688 ± 0.025	0.719 ± 0.026	0.723 ± 0.025	0.711 ± 0.034
τ	0.089 ± 0.030	0.092 ± 0.029	0.101 ± 0.028	0.098 ± 0.032	0.104 ± 0.036	0.104 ± 0.030
σ_8	0.761 ± 0.046	0.784 ± 0.048	0.857 ± 0.028	0.801 ± 0.039	0.785 ± 0.035	0.800 ± 0.037
n_s	0.956 ± 0.016	0.956 ± 0.017	0.964 ± 0.016	0.960 ± 0.013	0.957 ± 0.014	0.963 ± 0.020
n_{run}		–	–	–	–	-0.002 ± 0.015

to constrain the shape of the power spectrum of primordial density fluctuations and the amplitude of the matter power spectrum at intermediate scales σ_8. The main results are as follows.

(i) The high-resolution VHS Lyman α forest data are consistent to within 1σ with the three-year *WMAP* results but offer little additional constraining power because of the large error bars. The larger sample of mainly low-resolution Lyman α forest data (SDSS) as analysed by Viel & Haehnelt (2006) is also consistent to within 1σ with the new *WMAP* results. However, the joint analysis of the SDSS data gives about 2σ higher σ_8 and Ω_m values than those inferred from the new *WMAP* results alone.

(ii) The best-fitting values for a combined analysis are (1σ): $(\sigma_8, n_s) = (0.78 \pm 0.05, 0.96 \pm 0.02)$ and $(0.86 \pm 0.03, 0.96 \pm 0.02)$ for *WMAP* combined with high-resolution Lyman α forest data and *WMAP* combined with low-resolution Lyman α forest data as analysed by M05. The analysis of the SDSS data set as analysed by Viel & Haehnelt (2006) based on full hydrodynamical simulations gives $\sigma_8 = 0.80 \pm 0.04$.

(iii) The joint analysis of Lyman α forest data and the new *WMAP* data does not favour a running of the spectral index. The best-fitting value is $n_{run} = -0.002 \pm 0.015$ at $k = 0.002$ Mpc^{-1}.

(iv) Adding other CMB data sets, the 2dF Galaxy Survey and both Lyman α data sets, the constraints on the matter power spectrum become $(\sigma_8, n_s) = (0.78 \pm 0.03, 0.96 \pm 0.01)$.

The Lyman α forest data appear to be in reasonable agreement with the CMB and other data sets which probe the matter power spectrum at larger scales. The Lyman α forest data will thus continue to be used to measure parameters that affect the overall shape and/or the small-scale part of the matter power spectrum. For the near future further progress is, however, likely to be driven by a better understanding of the systematic uncertainties, rather than the compilation of larger data sets.

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