First Cosmological Constraints on Dark Energy from the Radial Baryon Acoustic Scale

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We present cosmological constraints arising from the first measurement of the radial (line-of-sight) baryon acoustic oscillations (BAO) scale in the large scale structure traced by the galaxy distribution. Here we use these radial BAO measurements at $z = 0.24$ and $z = 0.43$ to derive new constraints on dark energy and its equation of state for a flat universe, without any other assumptions on the cosmological model: $w = -1.14 \pm 0.39$ (assumed constant), $\Omega_m = 0.24^{+0.06}_{-0.05}$. If we drop the assumption of flatness and include previous cosmic microwave background and supernova data, we find $w = -0.974 \pm 0.058$, $\Omega_m = 0.271 \pm 0.015$, and $\Omega_k = -0.002 \pm 0.006$, in good agreement with a flat cold dark matter cosmology with a cosmological constant. To our knowledge, these are the most stringent constraints on these parameters to date under our stated assumptions.

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Before recombination, the Universe was filled by a plasma of coupled photons and baryons. On horizon crossing, cosmological fluctuations produced sound waves in this plasma and when recombination occurred, 380,000 years after the Big Bang, the distance covered by the sound wave was about 150 comoving Mpc. This is the so-called sound horizon $r_s$, also known as the BAO scale $r_{BAO}$. This signature can be found both in the cosmic microwave background (CMB) and large scale structure (LSS), so the baryon acoustic peak can be used as a standard ruler in the Universe. The value of $r_{BAO}$ depends on a few physical quantities, mostly the time to recombination and the time of matter domination, both of which are well known from measurements of CMB temperature anisotropies, i.e. through parameters $\Omega_m h^2$ and $\Omega_B h^2$, also in good agreement with large scale structure and primordial abundance measurements. Thus the spectrum of CMB fluctuations provide an accurate estimate of $r_{BAO} = 153 \pm 1.9$ Mpc, independent of the value of $H_0$, dark energy equation of state $w$ or the curvature of the Universe $\Omega_k$. At the same time the CMB also provides an angular measurement of the BAO scale, which together with $r_{BAO}$, can be used for geometrical test, such as the measurement of curvature.

A series of recent papers [2 3 4 5] have presented the clustering of Luminous Red Galaxies (LRG, see [6]) in the latest spectroscopic Sloan Digital Sky Survey (SDSS) data releases, DR6 & DR7, which include over 75,000 LRG galaxies and sample over 1 Gpc$^3$/h$^3$ to $z=0.47$. The last paper [5] focuses on the study of the 2-point correlation function $\xi(\sigma, \pi)$, separated in perpendicular $\sigma$ and line-of-sight $\pi$ directions to find a significant detection of a peak at $r \approx 110$ Mpc/h (for $H_0 = 100$ h Km/s), which shows as a circular ring in the $\sigma-\pi$ plane. There is also a significant detection of the peak along the line-of-sight (radial) direction both in sub-samples at low, $z=0.15-0.30$, and high redshifts, $z = 0.40 - 0.47$. The overall shape and location of the peak in the 2-point and 3-point function are consistent with its originating from the recombination-epoch baryon acoustic oscillations. This has been used to produce, for the first time, a direct measurement of the Hubble parameter $H(z)$ as a function of redshift. This is based on a calibration to the BAO scale measured in the CMB [1]. The values of $H(z)$ are then used in [3] to compare to other cosmological constraints that provide estimates for $H_0$.

Here, instead of calibrating the BAO distance, we will use the direct dimensionless measurement as a redshift scale (shown in Table [1]) to provide cosmological constraints that are independent of $H_0$. This is somehow similar to what is done in Percival et al. [7] for the spherically-averaged (i.e. monopole) BAO detection. Both the 2-Degree-Field Galaxy Redshift Survey 2dFGRS and SDSS spectroscopic redshift surveys have been used to constrain cosmological parameters at BAO dis-
correlations has been shown to be less than 10% on scales larger than 40 Mpc/h (see Fig. 2 of [15]). Thus, in practice, we can regard here the BAO measurements from the monopole as independent from the RBAO measurements.

Once the radial BAO scale has been measured [5], there are several possible approaches to extract the cosmological parameters solely from this measurement. Percival et al. [1] propose three possible ways. We have used two of them, that are described below. The third one uses the ratio of BAO scales at different redshifts. We have not used it, since we have the BAO scale at two different redshifts, so only one ratio can be constructed, and the degeneracy in the determination of cosmological parameters is larger using this approach.

To work with fiducial comoving scales, [6] uses a reference flat ΛCDM Hubble rate:

$$H_{ref}(z) = H_0 \sqrt{\Omega_m(1 + z)^3 + 1 - \Omega_m}$$

(1)

with $\Omega_m = 0.25$ to determine fiducial values for $r_{BAO}$ at two redshifts. Here, $\Delta z_{BAO}(z)$ are obtained from $r_{BAO}(z)$ in [5] as $\Delta z_{BAO}(z) = r_{BAO}(z)H_{ref}(z)/c$. Note that the measurements of $\Delta z_{BAO}(z)$ do not depend on $H_0$, since the dependences contained in $r_{BAO}(z)$ and $H_{ref}(z)/c$ cancel out.

Previous BAO (e.g. [7, 8]) analyses have only looked at the monopole, which is the average of $\xi(\sigma, \pi)$ over orientations:

$$\xi_0(r) = \int_0^1 \xi(\sigma, \pi) d\mu$$

(2)

where $r = \sqrt{\sigma^2 + \pi^2}$ and $\mu = \pi/r$. The BAO peak found by [5] was located at radial $\pi \approx 110$ Mpc/h for $\sigma < 5$ Mpc/h, which corresponds to $\mu > 0.999$. The contribution of radial modes with $\mu > 0.999$ to the monopole at $r = 110$ in the above integral is less than 1% even if we take the amplitude of $\xi(\sigma, \pi)$ to be 10 times larger in the radial $\pi$ direction than in the transverse $\sigma$ direction. Moreover, the covariance between radial and monopole

TABLE I: The BAO fiducial scale $r_{BAO}$ in the LOS direction calculated with a flat reference $H_{ref}(z)$ cosmology of $\Omega_m = 0.25$, for two redshift slices: $z_m$ is the respective pair-weighted mean redshift, and $\sigma_{st}$ and $\sigma_{sys}$ are the statistical and systematic errors on $r_{BAO}$ (from [5]). Here we use the direct $\Delta z_{BAO}$ measurement, shown in the sixth column, which relates to the fiducial scale as $\Delta z_{BAO} = r_{BAO}H_{ref}(z)/c$ and is independent of the value chosen for $H_{ref}(z)$. The last two columns show the corresponding errors.

| Sample, redshift range, Mpc/h | $z_m$ | $r_{BAO}$ | $\sigma_{st}$ | $\sigma_{sys}$ | $\Delta z_{BAO}$ | $\sigma_{st}$ | $\sigma_{sys}$ |
|-----------------------------|------|-----------|---------------|---------------|----------------|--------------|---------------|
| 0.15-0.30                   | 0.24 | 110.3     | 2.9           | 1.8           | 0.0407         | 0.0011       | 0.0007       |
| 0.40-0.47                   | 0.43 | 108.9     | 3.9           | 2.1           | 0.0442         | 0.0015       | 0.0009       |

We will derive cosmological constraints from the measured values of $\Delta z_{BAO}$ shown in Table I which can be expressed as

$$\Delta z_{BAO}(z_i) = \frac{H(z_i)r_s}{c},$$

(3)

where $r_s$ is the sound horizon at recombination. It is important to remark that the two measurements of $\Delta z_{BAO}$ are independent, due to the analysis strategy used in [5], which determines the BAO scale in two well separate intervals of redshift.

Throughout this letter, we will assume a standard Friedmann-Lemaître-Robertson-Walker cosmology having as free parameters the matter density $\Omega_m$, curvature $\Omega_k$, Hubble constant $H$ (with $H_0 = 100 h$ km/s/Mpc), and the parameter $w$ of the equation of state of dark energy, i.e. the ratio of its pressure to its density $\rho_p/\rho$. Unless otherwise specified, a constant $w$ is assumed, and thus, the standard ΛCDM model is recovered for $w = -1$. We will start by assuming also a flat Universe, $\Omega_k = 0$. In order to constrain the dark energy parameters $\Omega\Lambda \equiv 1 - \Omega_m$ and $w$, we can take two approaches:

a) We can express $r_s$ in [3] as

$$r_s = \frac{c}{(3\Omega_m H_0^2)^{1/2}} \left(\int_0^{1+z_m} \frac{da}{(a + a_0)^{1/2}(1 + a_0)^{3/2} a^{1/2}}\right)^{1/2}$$

(4)
TABLE II: Results from the cosmology fits with the radial BAO (RBAO) data and additional data sets assuming a constant equation of state parameter \( w \). In the data set a) the BAO radial data are used, and the values and errors of \( \Omega_m h^2 \) and \( \Omega_b h^2 \) from [11] are input into the computation of \( H(z_i)r_s \). For the data set b) the BAO radial data is combined with the measurement of \( l_A(z^*) \) from [11]. In all cases, the WMAP5 measurements within the appropriate cosmology model (flat, cosmological constant, etc.) are used, although the differences are minute. See text for details. The other rows combine the RBAO redshift scales presented in Table I with external data sets. All fits have values of \( \chi^2/N_{\text{ dof}} \) close to one. In particular, the fit with RBAO, WMAP5 and SNe data within a non-flat constant-\( w \) cosmology (last row) has \( \chi^2/N_{\text{ dof}} = 312/366 \).

| Data Set | \( \Omega_m \) | \( \sigma(\Omega_m) \) | \( \Omega_b \) | \( \sigma(\Omega_b) \) | \( w \) | \( \sigma(w) \) |
|----------|---------------|----------------|-------------|----------------|--------|-------------|
| RBAO a) | 0.242 ± 0.061 | 0.063 | 0 | — | −1.14 | +0.38 — 0.40 |
| RBAO b) | 0.248 ± 0.053 | 0 | 0 | — | −1.16 | +0.42 — 0.45 |
| RBAO + WMAP5 [11] | 0.274 ± 0.035 | 0.036 | 0 | — | −0.92 | +0.16 − 0.22 |
| RBAO + WMAP5 + SNe [16] | 0.268 ± 0.015 | 0.014 | 0 | — | −0.961 | +0.056 − 0.058 |
| RBAO a) | 0.249 ± 0.049 | 0.036 | −0.08 | +0.25 | −0.18 | −1 | — |
| RBAO b) | 0.223 ± 0.009 | 0.028 | ±0.058 | −1 | — |
| RBAO + WMAP5 [11] | 0.264 ± 0.017 | 0.016 | −0.0025 | ±0.0059 | −1 | — |
| RBAO + WMAP5 + SNe [16] | 0.271 ± 0.015 | 0.014 | −0.0026 | ±0.0060 | −1 | — |
| RBAO + WMAP5 [11] | 0.244 ± 0.062 | 0.052 | −0.0049 | ±0.0121 | −0.0661 | −1.13 | +0.37 − 0.39 |
| RBAO + WMAP5 + SNe [16] | 0.271 ± 0.015 | 0.014 | −0.0021 | ±0.0062 | −0.974 | +0.057 − 0.059 |

with

\[
 a_{eq} = \frac{\Omega_b h^2 (1 + 0.2271 N_{eff})}{\Omega_m h^2} \tag{5}
\]

with \( z_d \), the so-called drag redshift, written in terms of \( \Omega_b h^2 \) and \( \Omega_m h^2 \) (Eq. (3) in [11]), and take \( \Omega_b h^2 = 0.02273 \pm 0.0066 \) and \( \Omega_m h^2 = 0.1329 \pm 0.0064 \) from the five-year results of the Wilkinson Microwave Anisotropy Probe (WMAP5) [11] as external constraints (we could have also used determinations from nucleosynthesis or LSS measurements), and fix \( \Omega_b h^2 = 2.449 \times 10^{-5} \) and \( N_{eff} = 3.04 \). Note that the expression for \( \Delta z_{BAO}(z_i) \) in Eq. (2) is independent of \( H_0 \). Once the one-sigma WMAP5 constraints on \( \Omega_b h^2 \) and \( \Omega_m h^2 \) are included in the fit, the only remaining unknowns are \( \Omega_A(= 1 - \Omega_m) \) and \( w \). Since we have two independent \( \Delta z_{BAO}(z_i) \), we will be able to determine them.

b) Alternatively, we can use as external constraints the measurements by WMAP5 of the ratio \( l_A(z^*) \) between the distance to the last scattering surface and \( r_s(z^*) \) and of \( z^* \) itself, \( l_A(z^*) = 302.14 \pm 0.87 \) and \( z^* = 1090.5 \pm 1.0 \) with a \( \sim 40 \% \) positive correlation, when assuming a flat CDM model with constant equation of state \( w \). Again, \( H_0 \) cancels out and we are left with only \( \Omega_m \) and \( w \) as unknowns, which we then proceed to determine.

In all cases, a frequentist \( \chi^2 \) fit including correlations is applied to the data, using the publicly available Minuit code [17] for minimization and contour calculation. Systematic errors in \( \Delta z_{BAO}(z_i) \) have been neglected, being subdominant (see Table I) and relatively uncertain. Including them does not change the results significantly. The results obtained for \( \Omega_m \) and \( w \) and their 1-\( \sigma \) errors, \( \sigma(\Omega_m) \) and \( \sigma(w) \), are shown in rows 1 and 2 of Table I. Both determinations, a) and b), are consistent between them and in agreement with \( \Lambda \)CDM. The two-dimensional constraints at 68\% CL can be seen in Fig. I.

Next, we have combined the results obtained from the radial BAO scale with the full CMB distance constraints, using the WMAP5 measurements of the shift parameter \( R(z^*) \), the acoustic scale \( l_A(z^*) \) and the redshift at decoupling \( z^* \) presented in Table 10 of [11], and the covariance matrix in Table 11 therein. We have also added the supernovae set compiled by Kowalski et al. [16], which can be found in [22]. We have taken their data covariance matrix in Table I. The two-dimensional constraints at 68\% CL which are shown in Fig. I.
matrix without systematical errors. Adding systematics does not change the results qualitatively. The results of the combination assuming flatness can be seen in rows 3 and 4 of Table II. We determine the equation of state parameter $w$, assumed constant, to be consistent with a cosmological constant Universe with a precision around 5%.

If, instead, we assume the $\Lambda$CDM model and drop the assumption of flatness, we obtain the results in rows 5–8 of Table II, which show consistency with a flat Universe assumption of flatness, we obtain the results in rows 5–8 of Table II. We determine the equation of state $w_\Lambda$ for dark energy.

In summary, we have determined for the first time the cosmological parameters $\Omega_m$ and $w$ using the radial BAO scale, to be $\Omega_m = 0.24^{+0.06}_{-0.05}$ and $w = -1.14 \pm 0.39$. These results are perfectly consistent with the expectations of the $\Lambda$CDM cosmology. Moreover, when these results are combined with the cosmological distance constraints coming from the CMB [1] and type-Ia supernovae [19], we measure $\Omega_m = 0.271 \pm 0.015$, $\Omega_k = -0.002 \pm 0.006$, and $w = -0.974 \pm 0.058$. The result is in good agreement with a flat $\Lambda$CDM cosmology, and shows that the determination of the BAO scale is consistent with all the other cosmological measurements.

In the future, currently planned BAO surveys like Baryon Oscillations Sloan Survey (BOSS) [23] or Physics of the Accelerating Universe (PAU) [20] will measure radial BAOs with greater precision up to redshifts close to $z = 1$, producing more stringent constraints on the properties of dark energy.

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