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Model-independent dark energy equation of state from unanchored baryon acoustic oscillations

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ABSTRACT

Ratios of line of sight baryon acoustic oscillation (BAO) peaks at two redshifts only depend upon the average dark energy equation of states between those redshifts, as the dependence on anchors such as the BAO scale or the Hubble constant is canceled in a ratio. As a result, BAO *ratios* provide a probe of dark energy which is independent of both the cosmic distance ladder and the early evolution of universe. In this note, we use ratios to demonstrate that the known tension between the Lyman alpha forest BAO measurement and other probes arises entirely from recent ($0.57 < z < 2.34$) cosmological expansion. Using ratios of the line of sight Lyman alpha forest and BOSS CMASS BAO scales, we show that there is already more than 3σ tension with the standard ΛCDM cosmological model which implies that either (i) The BOSS Lyman alpha forest measurement of the Hubble parameter was too low as a result of a statistical fluctuation or systematic error or else (ii) the dark energy equation of state falls steeply at high redshift.

1. Motivation

The location of the baryon acoustic oscillation peak provides a standard ruler which can and has been used to measure the expansion of the Universe. This ruler can be observed along both the angular and line of sight directions. However limited statistics implied that, until recently, precise measurements of this peak were only available for a weighted average of the line of sight and angular directions. Using such a weighted average, studies typically found good agreement with the standard ΛCDM cosmological model.

This situation has changed with the separate measurements of the line of sight and angular peaks at $z = 2.3$ by the BOSS survey [1], which is in mild tension with ΛCDM predictions when combined with data from other probes. There have been numerous investigations of this tension, and distinct proposals for its resolution, but it is unclear just which of these should be chosen [2].

The goal of the present paper is quite modest. Very recently the BOSS collaboration has released precise measurements of the line of sight and angular baryon acoustic oscillation peaks at low redshifts [3]. We will use this new data to show that the tension, should it be confirmed by future observations, arises entirely from the acceleration of the Universe between $z = 0.57$ and $z = 2.34$, thus eliminating many of the possible sources of the discrepancy suggested in earlier papers.

Our demonstration will be very elementary but also very model independent, and in fact entirely independent of the history of the Universe before $z = 2.34$. It will be based on a ratio of Hubble parameters arising from a ratio of BAO scales. Such ratios have been considered in the past in similar contexts, although in general with additional assumptions, for example Ref. [4] assumes that the Universe never accelerated. We make no assumptions about either the expansion history nor about the functional form of the dark energy equation of state. We stress that such a general analysis is only possible now as a result of the precise anisotropic baryon acoustic oscillation measurement in Ref. [3], indeed the larger uncertainties in older data implied that similar analyses revealed no tension [5].

2. Baryon acoustic oscillations and model dependence

The spatial two-point correlation function of the density of baryons has a peak, the baryonic acoustic oscillation (BAO) peak, at a comoving scale r_s which is believed to be about 150 Mpc. As baryons on these scales have been nonrelativistic since shortly after recombination, the location of the peak in comoving coordinates has not changed. The location of the peak therefore provides a universal ruler, with a constant comoving length at distinct redshifts through nearly all of cosmic history [6].

Correlations may be observed for objects separated along the line of sight, whose distances are determined by redshifts z, or by objects separated perpendicular to the line of sight, whose distances are determined using their angular separation. In this

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note we will be interested in the first case. The two-point function in redshifts has a peak at

$$\Delta z = \frac{r_s H(z)}{c} \tag{2.1}$$

where $H(z)$ is the Hubble parameter at redshift z. Therefore BAO surveys in principle can determine the combination $r_s H(z)$ for various redshifts z.

In practice, surveys accumulate data over a range of redshifts and package their results in terms of just one redshift for each sample. This packaging requires the assumption of a fiducial cosmological model, however the dependence on the choice of model is quite small. Similarly the position of the peak is determined by comparing the matter correlation functions with simulations based on a fiducial cosmological model, but due to nuisance parameters included in this analysis, the result is again quite robust with respect to changes in the fiducial model. With these caveats understood, the resulting determination of $r_s H(z)$ is independent of the assumed cosmological model.

On the other hand, the value of r_s does depend on the cosmological model. For example, as has been stressed in Ref. [7], while the 2013 Planck results [8], combined with polarization from WMAP, report a measurement of r_s with an uncertainty of only 0.4% assuming a standard ΛCDM cosmology, this uncertainty increases to 2.3% if one modifies ΛCDM only by letting N_{eff}, the effective number of light degrees of freedom, float freely. Furthermore, fixing N_{eff} to the ΛCDM value leads to a 2.7% shift in the central value of r_s. While this model dependence is not large, it is already larger than the uncertainty obtained by some BAO measurements.

More generally, there are two ways in which r_s may be modified. First, one may fix the sound horizon size at recombination, fixing the locations of the acoustic peaks in the cosmic microwave background (CMB) power spectrum, but use an unconventional evolution of the sound horizon during the drag epoch such as the analysis of the streaming of supersonic baryons in Ref. [9]. Second, one may modify the sound horizon at recombination, compensating for the shift in the angular size of the CMB acoustic peaks by modifying, for example, the evolution of dark energy at recent times to yield an angular diameter distance to recombination which changes proportionally r_s.

A modification of the acoustic horizon size at recombination can be achieved in two distinct ways, one can either modify the pre-recombination expansion $a(t)$ or else one may modify the speed of sound in the primordial plasma. An exotic cosmological model may do either of these. As an example of the first, note that standard inflationary cosmology asserts that the energy density of the Universe was twice dominated by dark energy, with no explanation as to its nature. A third epoch of dark energy, well before matter–radiation equality, with negative energy density could lead to a brief stall in the expansion and so yield an increase in r_s. As an example of the second mechanism, one may add charged matter in equilibrium with the plasma and with a density which is comparable to or even exceeds that of baryonic matter. As the speed of sound in the plasma is inversely proportional to $\sqrt{3+R}$ where R is the ratio of the energy density of charged matter to photons, this would increase R and so decrease the speed of sound and so the sound horizon size. Ordinarily such matter could be excluded by comparing the heights of the even and odd acoustic peaks in the CMB power spectrum. However such a contribution could be minimized if the additional matter component is unstable and decays sufficiently before matter–radiation equality. In a yet more extreme model, one may not assert that it decays, but rather adjust the primordial fluctuation spectrum to compensate for this effect. All of these modifications (except for the freely floating N_{eff}) are rather unnatural, but they serve to highlight that the precision with which r_s is thought to be known results not from a direct measurement, but rather from the combination of a measurement with a wide array of assumptions which are yet to be tested.

Table 1
Measurements of $H(z)r_s/c$.

Effective redshift z	Measured $H(z)r_s/c$
$z = 0.32$	0.0388 ± 0.0021
$z = 0.57$	0.0485 ± 0.0013
$z = 2.34$	0.109 ± 0.002

3. Ratios of BAO measurements

Fortunately it is possible to use the radial BAO peak without knowing r_s. If one knows the location of the peak at two different redshifts z_1 and z_2, then one obtains $r_s H(z_1)/c$ and $r_s H(z_2)/c$. While each individually depends on the cosmological model through r_s, the ratio only depends on the expansion history in the time since these measurements. Ratios of the tangential BAO peak similarly yield robust determinations of ratios of angular distances, which depend on integrals of $1/H(z)$ and the spatial curvature, however in this note we will not use them. Combining ratios of angular and line of sight BAO measurements is equivalent to using only ratios of line of sight measurements plus Alcock–Paczynski tests [10] on the BAO scale at each redshift.

We will use the final results from the Baryon Oscillation Spectroscopic Survey (BOSS) [3] which provide measurements of $H(z)$ for samples of galaxies in two redshift groups. The closer galaxy sample, called LOWZ, has an effective redshift of $z = 0.32$ while the farther CMASS sample has an effective redshift of $z = 0.57$. These results appear quite consistent with the standard ΛCDM paradigm. However we will also use BOSS measurements of the BAO in the autocorrelation of masses traced by the Lyα forest absorption of light from quasars [1] and the cross-correlation of the mass densities traced by the Lyα forest and quasars [11]. These determine $H(z)$ at an effective redshift of $z = 2.34$. The autocorrelation and cross-correlation results for $H(z = 2.34)$ were already combined in Ref. [1]. These results are all summarized in Table 1. A number of other BAO measurements are not included in our analysis either because they do not decompose the BAO size into a line of sight and tangential component and/or because their survey volume overlaps with that of BOSS.

Tension between the $z = 2.34$ BAO peak location and the standard cosmological model, at the 2–3σ level, was noticed immediately [1] and has been the subject of numerous investigations. While there seems to be no standard variation of ΛCDM that removes this tension [2], by combining it with various cosmological datasets it has been noted by several authors that it suggests that the dark energy density becomes negative at high redshift [1,12]. In general the space of parameters is large enough that authors find that this measurement supports models that had previously been focuses of their research, such as modified gravity [13] or a zero active mass model [14]. Needless to say, *any* measurement of the dark energy equation of state as a function of redshift $w(z)$ is consistent with an infinite number of dark energy models, such as generalized galileons [15] and braiding models [16]. However, robust evidence that dark energy once contributed negative energy to the universe would imply a conceptual restriction on dark matter models, not just a fitting of parameters. Therefore it is important to determine just how robust the evidence for a negative energy density really is.

4. Calculation

In our analysis we will assume that the universe at large scales is homogeneous and isotropic and is described by Einstein's equations coupled to a perfect fluid with density ρ and pressure p, which allow us to define an equation of state $w = p/\rho$. Note that even many modified gravity models, such as $f(R)$ gravity, can be re-expressed as Einstein gravity coupled to matter [17,18] and