BOSS: THE BARYON OSCILLATION SPECTROSCOPIC SURVEY

Probing the Physics of Dark Energy with Baryon Acoustic Oscillations

Submitted by
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The acceleration of the expansion of the Universe poses the most profound question in physical science today. Even the most prosaic explanations of cosmic acceleration demand the existence of a pervasive new component of the Universe ("dark energy") with exotic physical properties. More extreme alternatives include extra spatial dimensions or a breakdown of General Relativity on cosmological scales. Because of the fundamental importance of the dark energy problem, the Dark Energy Task Force (DETF) recommended an aggressive, multi-pronged experimental attack. Their report focuses on the four leading methods for probing cosmic expansion and the effects of dark energy: Type Ia supernovae, galaxy clusters, weak gravitational lensing, and baryon acoustic oscillations (BAO). They note that BAO measurements are believed to be the method "least affected by systematic uncertainties, and for which we have the most reliable forecasts of resources required to accomplish a survey of chosen accuracy." This brief White Paper describes the Baryon Oscillation Spectroscopic Survey (BOSS), a Stage III experiment (in DETF parlance) that will achieve the first measurement of the BAO absolute cosmic distance scale with 1% precision.

For the first 400,000 years after the big bang, photons and baryons were tightly coupled and acted essentially as a single fluid with sound speed slightly over half the speed of light. Pressure waves that propagated in this fluid before decoupling imprinted a characteristic scale on the distribution of matter, and the absolute length of this "standard ruler" can be calculated to high accuracy using cosmological parameter values that are tightly constrained by measurements of the cosmic microwave background. This scale can be detected in the late-time distribution of matter and galaxies as an enhancement of clustering at 150 Mpc (500 million light-year) separation. Because the acoustic scale is so much larger than the scale of non-linear gravitational collapse, the method is highly robust. The best theoretical studies currently available imply that shifts in the BAO scale caused by non-linear growth of fluctuations and bias between galaxies and dark matter are 0.5% or less, so we need only calculate these non-linear corrections with moderate accuracy to bring systematic errors well below the level of our forecast statistical uncertainties.

The detection of the acoustic oscillation scale is one of the signature accomplishments of the SDSS (see Fig. 1). The SDSS detection used a spectroscopic sample of 60,000 color-selected Luminous Red Galaxies (LRGs) to measure the absolute distance to redshift $z = 0.35$ with precision of 4%, substantially improving constraints on cosmological parameters such as the dark energy density and the curvature of space.

BOSS was proposed in 2006 to achieve a seven-fold improvement over the full SDSS and SDSS-II large-scale structure data set. In a competitive, peer-reviewed process, BOSS was awarded five years of survey time on the SDSS 2.5m telescope by the Astrophysical Research Consortium (ARC). BOSS builds on the substantial existing hardware and software infrastructure of SDSS, requiring only a modest upgrade of the existing spectrographs with LBNL CCDs and new gratings to achieve higher throughput, and more fibers to increase the target density. This upgrade will be completed by mid-2009, when BOSS will commence a 5-year redshift survey (2009 - 2014) of 1.5 million LRGs, reaching to redshift $z = 0.7$. Figure 2 illustrates the anticipated precision of the BOSS LRG

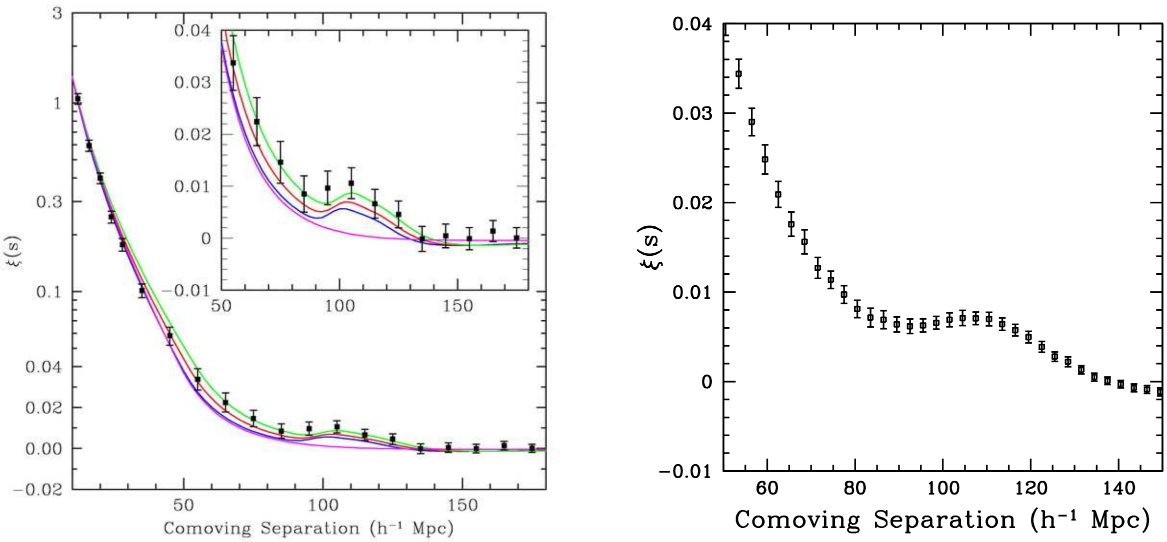

Figure 1: **Fig. 1 (left):** The first detection of BAO by the Sloan Digital Sky Survey. Points show the measured correlation function of luminous red galaxies (LRGs) as a function of comoving separation. The enhancement of clustering at $100h^{-1}$ Mpc (approximately 150 Mpc for $h = 0.7$) reveals the imprint of baryon acoustic oscillations. Curves show theoretical predictions for different values of the baryon-to-dark matter ratio. Fitting the peak of the correlation function bump yields the BAO scale, with 1σ precision of 4% in this measurement. **Fig. 2 (right):** Anticipated precision of the correlation function measurement from the LRG sample of the Baryon Oscillation Spectroscopic Survey. These measurements will allow determination of the angular diameter distance d_A with errors of 1.0% at $z = 0.35$, and 1.1% at $z = 0.6$, and determination of the Hubble parameter $H(z)$ with errors of 1.8% and 1.7% at the same redshifts. BOSS will also use the distribution of neutral hydrogen absorption in the spectra of high-redshift quasars to measure the BAO scale, determining d_A to 1.5% and $H(z)$ to 1.8% at $z = 2.5$.

measurement of the BAO feature in the galaxy correlation function. Because we can measure both the angular size and the line-of-sight separation of the BAO scale, we obtain measurements of both the angular diameter distance $d_A(z)$ and the Hubble expansion parameter $H(z)$, which provide complementary information about dark energy and space curvature. Our forecasts show that the LRG sample will yield 1σ errors on d_A of 1.0% at $z = 0.35$ and 1.1% at $z = 0.6$ and corresponding $H(z)$ errors of 1.8% and 1.7%. All current evidence indicates that these errors will be dominated by statistical rather than systematic uncertainties.

The BOSS LRG survey will be the definitive low redshift BAO experiment for the foreseeable future, reaching within a factor of 2 of the full-sky cosmic variance errors for $z < 0.5$. The BOSS spectroscopic survey covers 1/4 of the sky with precise redshifts of strongly clustered tracers, with sampling density sufficient to extract nearly all of the BAO information. Even a full-sky photometric redshift survey cannot match the BOSS BAO precision at $z < 0.7$ because of the loss of BAO information due to imprecise redshifts. Photometric surveys also cannot measure $H(z)$ because they do not resolve the BAO peak in the line-of-sight direction. In contrast to Type Ia supernovae, which are calibrated by objects in the local Hubble expansion, the BAO scale is anchored in the cosmic microwave background at $z = 1100$, so the leverage of BAO measurements on dark energy parameters is generally strongest at low redshift.

In addition to the LRG survey, BOSS will measure the BAO scale at $z \approx 2.5$ using neutral hydrogen gas absorption in the spectra of 160,000 high-redshift quasars (QSOs). Because each quasar spectrum effectively probes hundreds of points along its line of sight, this is a very efficient method for mapping large scale structure at high redshift. Our forecasts show that the quasar absorption survey will yield 1.5% errors on $d_A(z)$ and $H(z)$ at $z = 2.5$. The spectroscopic targets for both the LRG and quasar surveys can be efficiently selected from existing SDSS multi-color imaging.

Table 1 makes clear that BOSS will provide an impressive advance over our current and near-future state of knowledge. In combination with the results of ongoing Stage II experiments, BOSS BAO measurements will improve the DETF figure-of-merit by a factor of 2.3 relative to Stage II alone. (The figure-of-merit is inversely proportional to the expected errors on the equation-of-state parameter w_p and its first derivative w_a in a 2-parameter dark energy model.) The QSO survey substantially tightens the parameter constraints, in large part because it sharpens the constraint on space curvature. The comparison with other proposed BAO experiments is given in the Table; BOSS is the most powerful experiment as measured by the FoM, with only WFMOS (which would come much later than BOSS) coming close.

Including information from the broad-band shape of the clustering power spectrum in addition to the BAO scale itself more than doubles this performance. Theoretical modeling of non-linear effects is required to extract parameter constraints from the broad-band spectrum, but the systematic uncertainties in this approach are probably no larger than those facing weak lensing and galaxy cluster analyses. BOSS will improve constraints on the curvature of space (Ω_k) by a factor of five, allowing much more powerful tests of the inflationary prediction of a flat universe. The high-redshift measurement of $H(z)$ from the quasar absorption survey is a powerful test of "early dark energy" models, in which dark energy is already a significant fraction of the total energy density at $z = 2.5$.

The value of BOSS is even greater when considered in combination with other planned experiments. BAO and supernovae are the two purely geometrical methods for probing cosmic expansion, allowing careful cross-checks for systematic uncertainties at the 1% level. The curvature measurement from BOSS breaks an important degeneracy in supernova dark energy constraints, and supernova surveys can transfer the absolute distance calibration from the BOSS LRG survey to higher and lower redshifts. The BOSS measurements also complement measurements that use weak gravitational lensing or the abundance of massive galaxy clusters, since these depend on both the geometrical expansion and the gravitational growth of inhomogeneities. Comparisons of geometrical and growth-based measures are the key to distinguishing dark energy models from models in which cosmic acceleration arises from a modification of General Relativity. On its own, the combination of BOSS with SDSS imaging should allow 1-2% measurements of the amplitude of dark matter clustering via galaxy-galaxy weak lensing, and this precision can be improved once deeper imaging surveys such as Pan-STARRS or LSST become available over the same area.

The SDSS, both the original 5-year program and its ongoing 3-year extension (SDSS-II), has made enormous contributions across a wide span of astronomical fields, including key contributions that have helped define the field of precision cosmology. Along the way it has exemplified a new mode of astronomical discovery, similar in many ways to the approach of experimental particle physics, with a large team of scientists cooperating in a systematic survey to produce large, publicly available data sets that support a rich variety of investigations.

BOSS is the flagship survey of SDSS-III, a proposed six-year program that will extend the

Expt.	h	Ω_K	w_0	w_p	w_a	FoM
BOSS LRG	0.008	0.0028	0.089	0.032	0.366	86
BOSS LRG+QSO	0.008	0.0019	0.076	0.029	0.279	**122**
+WL	0.008	0.0017	0.068	0.026	0.227	172
+CL	0.008	0.0018	0.071	0.023	0.244	177
+SN	0.006	0.0019	0.052	0.023	0.220	199
+WL+CL+SN	0.005	0.0016	0.046	0.018	0.164	331
WiggleZ	0.012	0.0028	0.099	0.035	0.430	66
HETDEX	0.015	0.0021	0.098	0.034	0.417	70
WFMOS	0.011	0.0017	0.083	0.033	0.323	95
Including Broad-Band Power Information:						
BOSS LRG+QSO	0.007	0.0015	0.065	0.016	0.240	257
+WL+CL+SN	0.005	0.0013	0.041	0.014	0.150	479

Table 1: A comparison of the abilities of current and next generation BAO experiments to constrain the expansion rate and curvature of space and the redshift dependent equation of state of dark energy. All constraints assume the DETF forecasts for "Stage II" experiments, which alone have a FoM of 53, as a prior. Lines $3-6$ show the additional gains from adding Stage III weak lensing, cluster, and supernova constraints, using the DETF "optimistic" forecasts. BAO constraints in the first two sections of the table include only the acoustic scale information and are therefore conservative; the final two lines show BOSS forecasts that also incorporate broad-band power information.

legacy of the SDSS and take it into new scientific realms. The three other surveys that comprise SDSS-III use observing time not required for BOSS to carry out studies of the Milky Way and extra-solar planetary systems; each of these surveys is extraordinarily powerful in its own right. BOSS leverages the existing SDSS telescope, instruments, and software, and the experience of the team that created the SDSS and pioneered the field of BAO cosmology. By doing so, it can achieve the definitive low redshift measurement of baryon acoustic oscillations and obtain unique constraints on dark energy within the time and cost scale of a Stage III dark energy experiment. The total budget for all four surveys included in the SDSS-III project is $47M in escalated, as-spent dollars, including contingency. The project will be funded from four sources: the Sloan Foundation, which has already pledged $7M in early funding, membership contributions from the more than 20 institutions that have indicated their interest, and support from NSF and DOE, where proposals are pending.

A much more detailed description of BOSS, including technical background of the forecasts reported here, can be found in the SDSS-III project description available at `http://www.sdss3.org`.