Measuring Cosmic Distances with the Baryon Acoustic Oscillations

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The clustering of matter on large scales has two different roles in modern cosmology.

- Provides a window into the early Universe, probing the composition and forces as a function of time.
- Provides the underlying scene for the formation of galaxies, clusters, and other luminous structures. A recasting of the role of environment.

The theory of large-scale structure unites many different observations:

- Cosmic microwave background anisotropies
- Galaxy clustering & clusters of galaxies
- Lyman $n$ forest & other IGM tracers
- Weak lensing
- Galaxy formation and evolution
Clustering Regimes

- Cosmological perturbations begin small but grow over time. When they reach order unity, they collapse into halos.

- Large scales (>30 Mpc)
  - Linear perturbation theory, simple outcome of clustering bias.
  - Window into early Universe.

- Small scales (<few Mpc) and quasi-linear scales (3-30 Mpc)
  - Non-linear gravity, increasingly complicated segregation of light and mass.
  - Scene for galaxy formation.
Cosmic Concordance

- Last decade of observations has been a stunning success in cosmology.
  - CMB Anisotropies
  - LSS from SDSS & 2dF
  - Discovery of dark energy with SNe
  - Predictive model matches many observations across wide range of scales from 1 second after the Big Bang until today.

- Standard cosmological model now established and offers opportunity to pursue precision measurements.
  - Dark Energy: cosmological constant or not? If not, what?
  - Dark Matter, deviations from CDM
  - Primordial spectrum
  - Primordial non-Gaussianity
  - Isocurvature admixtures
  - Neutrino Masses
  - Gravitational waves from the early Universe
  - Particle decays
Outline

- Galaxy and Lyman $n$ forest power spectra.
- Baryon acoustic oscillations as a standard ruler.
  - Acoustic oscillations in the non-linear regime.
- Detection of the acoustic signature in the SDSS Luminous Red Galaxy sample at $z=0.35$.
  - Cosmological constraints therefrom.
- Present the Baryon Oscillation Spectroscopic Survey and SDSS-III.
SDSS Galaxy Clustering

- Power spectrum has been computed in several different ways and different teams within the project.
- Marvelous match to adiabatic CDM model.

Tegmark et al. (2006)
Matter-Radiation Equality

- CDM theories predict a deficit of small-scale power, due to the lack of growth of sub-horizon perturbations during the radiation-dominated era.
- Turnover depends on scale of horizon at matter-radiation equality and hence on the amount of matter.
- More matter means more small-scale growth, or less large-scale power relative to small-scale.
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Data from Tegmark et al. (2006)
Absorption by neutral hydrogen along the line of sight to high-z quasars traces the intergalactic density field.

- Measure the amplitude and spectral slope of clustering on small scales \((k \sim 1h \text{ Mpc}^{-1})\).
  - Still essentially in the linear regime.

- The extra lever arm sharply improves the constraints on cosmological parameters.

McDonald et al. (2004)
Constraints on Inflation

- Accuracy on “normal” parameters reaching point that we can search for relics of inflation.
  - Gravitational waves
  - Running of spectral tilt

Seljak et al. (2004)
Although there are fluctuations on all scales, there is a characteristic angular scale.
Acoustic Oscillations in the CMB

Angular Scale

TT Cross Power Spectrum

\[ I(l+1)C_l/2\pi (\mu K^2) \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \]

\[ 0 \quad 1000 \quad 2000 \quad 3000 \quad 4000 \quad 5000 \quad 6000 \]

Multipole moment \((l)\)

Angular Scale

90° 2° 0.5° 0.2°

WMAP team (Bennett et al. 2003)
Before recombination:
- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Perturbations oscillate as acoustic waves.

After recombination:
- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at $t_{\text{rec}}$ affects late-time amplitude.

Big Bang

Recombination

$z \sim 1000$

$\sim 400,000$ years

Neutral

Time

Today
Sound Waves

- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.
A Statistical Signal

- The Universe is a superposition of these shells.
- The shell is weaker than displayed.
- Hence, you do not expect to see bullseyes in the galaxy distribution.
- Instead, we get a 1% bump in the correlation function.
Remember: This is a tiny ripple on a big background.

Based on CMBfast outputs (Seljak & Zaldarriaga). Green’s function view from Bashinsky & Bertschinger 2001.
Acoustic Oscillations in Fourier Space

- A crest launches a planar sound wave, which at recombination may or may not be in phase with the next crest.
- Get a sequence of constructive and destructive interferences as a function of wavenumber.
- Peaks are weak — suppressed by the baryon fraction.
- Higher harmonics suffer from Silk damping.
A Standard Ruler

- The acoustic oscillation scale depends on the sound speed and the propagation time.
  - These depend on the matter-to-radiation ratio ($n_m h^2$) and the baryon-to-photon ratio ($n_b h^2$).
- The CMB anisotropies measure these and fix the oscillation scale.
- In a redshift survey, we can measure this along and across the line of sight.
- Yields $H(z)$ and $D_A(z)$!
Distances to Acceleration

- Cosmological distance measurements are the entrance to a deep mystery: the acceleration of the expansion rate of the Universe.
  - Cosmological constant?
  - A new force of nature?
  - Modification of gravity?
  - Signature of quantum gravity or extra dimensions?
- The acoustic oscillation method is now a major part of our plans for the study of the dark energy.
Galaxy Redshift Surveys

- Redshift surveys are a popular way to measure the 3-dimensional clustering of matter.

- But there are complications from:
  - Non-linear structure formation
  - Bias (light ≠ mass)
  - Redshift distortions

- Partially degrade the BAO peak, but systematics are small because this is a very large preferred scale.
Nonlinear Structure Formation and the BAO

- The acoustic signature is carried by pairs of galaxies separated by 150 Mpc.

- Nonlinearities push galaxies around by 3-10 Mpc. Broadens peak, making it hard to measure the scale.

- Non-linearities are increasingly negligible at $z>1$. Linear theory peak width dominates.

Seo & DJE (2005); DJE, Seo, & White (2007)
Fixing the Nonlinearities

- Most of the non-linear degradation is due to bulk flows. These are produced by the same large-scale structure that we are measuring for the BAO signature.
- Map of galaxies tells us where the mass is that sources the gravitational forces that create the bulk flows.
- Can run this backwards and undo most non-linearity.
- Restore the statistic precision available per unit volume!

DJE, Seo, Sirko, & Spergel (2007)
Shifting the Acoustic Scale

- Moving the acoustic scale requires net infall on 100 $h^{-1}$ Mpc scales. Much smaller than random motions on small-scales. Expect infalls are <1%.
- We have used $320h^{-3}$ Gpc$^3$ of PM simulations to compute the non-linear shifts.
- Find shifts of 0.25% at z=1.5 to 0.5% at z=0.3.
- These shifts are predictable and hence removable! This is just large-scale gravitational flows.
- Galaxy bias enters through the relation of galaxies to these flows.

Seo, Siegel, DJE, & White (2008)
Virtues of the Acoustic Peaks

- The acoustic signature is created by physics at z=1000 when the perturbations are 1 in $10^4$. Linear perturbation theory is excellent.

- Measuring the acoustic peaks across redshift gives a geometrical measurement of cosmological distance.

- The acoustic peaks are a manifestation of a preferred scale. Still a very large scale today, so non-linear effects are mild and dominated by gravitational flows that we can simulate accurately.
  - No known way to create a sharp scale at 150 Mpc with low-redshift astrophysics.

- Measures absolute distance, including that to z=1000.

- Method has intrinsic cross-check between $H(z)$ & $D_A(z)$, since $D_A$ is an integral of $H$. 


SDSS Luminous Red Galaxies
Large-Scale Correlations

CDM with baryons is a good fit: $n^2 = 16.1$ with 17 dof.

Pure CDM rejected at $n^2 = 11.7$

Warning: Correlated Error Bars

Acoustic series in $P(k)$ becomes a single peak in $n(r)$!

Pure CDM model has no peak.
Equality scale depends on $(n_m h^2)^{-1}$.

Acoustic scale depends on $(n_m h^2)^{-0.25}$.

$n_m h^2 = 0.12$

$n_m h^2 = 0.13$

$n_m h^2 = 0.14$
Cosmological Constraints

- Pure CDM degeneracy
- Acoustic scale alone
- WMAP 1n
Essential Conclusions

- SDSS LRG correlation function does show a plausible acoustic peak.
- Ratio of $D(z=0.35)$ to $D(z=1000)$ measured to 4%.
  - This measurement is insensitive to variations in spectral tilt and small-scale modeling. We are measuring the same physical feature at low and high redshift.
- $n_m h^2$ from SDSS LRG and from CMB agree. Roughly 10% precision.
  - This will improve rapidly from better CMB data and from better modeling of LRG sample.
- $n_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137 n_K$. 
We have also done the analysis in Fourier space with a quadratic estimator for the power spectrum.

Also FKP analysis in Percival et al. (2006, 2007).

The results are highly consistent.

• $n_m = 0.25$, in part due to WMAP-3 vs WMAP-1.

Tegmark et al. (2006)
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SDSS-III

- SDSS-III is the next phase of the SDSS project, operating from summer 2008 to summer 2014.
- SDSS-III has 4 surveys on 3 major themes.
  - BOSS: Largest yet redshift survey for large-scale structure.
  - SEGUE-2: Optical spectroscopic survey of stars, aimed at structure and nucleosynthetic enrichment of the outer Milky Way.
  - APOGEE: Infrared spectroscopic survey of stars, to study the enrichment and dynamics of the whole Milky Way.
  - MARVELS: Multi-object radial velocity planet search.
- Extensive re-use of existing facility and software.
- Strong commitment to public data releases.
Baryon Oscillation Spectroscopic Survey (BOSS)

- Definitive study of the low-redshift acoustic oscillations. 10,000 deg$^2$ of new spectroscopy from SDSS imaging.
  - 1.5 million LRGs to $z=0.8$, including 4x more density at $z<0.5$.
  - 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at $z=0.35$ and $z=0.6$.
  - Straight-forward extension of current program.
- Simultaneous project to discover the BAO in the Lyman $\alpha$ forest.
  - 160,000 quasars. 20% of fibers.
  - 1.5% measurement of distance to $z=2.3$.
  - Higher risk but opportunity to open the high-redshift distance scale.
Seeing Sound in the Lyman $\alpha$ Forest

- The Lyman forest tracks the large-scale density field, so a grid of sightlines should show the acoustic peak.
- This may be the cheapest way to measure the acoustic scale at $z>2$.
  - Require only modest resolution ($R=250$) and low S/N.
- Bonus: the sampling is better in the radial direction, so favors $H(z)$.

White (2004); McDonald & DJE (2006)

Neutral $H$ absorption observed in quasar spectrum at $z=3.7$
Cosmology with BOSS

- BOSS measures the cosmic distance scale to 1.0% at $z = 0.35$, 1.1% at $z = 0.6$, and 1.5% at $z = 2.5$. Measures $H(z = 2.5)$ to 1.5%.

- These distances combined with Planck CMB & Stage II data gives powerful cosmological constraints.
  - Dark energy parameters $w_p$ to 2.8% and $w_a$ to 25%.
  - Hubble constant $H_0$ to 1%.
  - Matter density $\rho_m$ to 0.01.
  - Curvature of Universe $n_k$ to 0.2%.
  - Sum of neutrino masses to 0.13 eV.

- Superb data set for other cosmological tests, as well as diverse extragalactic applications.
Conclusions

- SDSS has fulfilled its goals as a large-scale structure survey in many ways, some expected, others unexpected.
  - Diverse and compelling support for the standard cosmological model.

- Acoustic oscillations provide a robust way to measure $H(z)$ and $D_A(z)$.
  - Clean signature in the galaxy power spectrum.
  - Can probe high redshift; can probe $H(z)$ directly.

- SDSS LRG sample uses BAO to measure $D_A(z=0.35)$ to 4%.

- SDSS-III will push to 1% with the definitive study of the low-redshift BAO and will open the study of dark energy at high redshift.
BOSS Instrumentation

"Straightforward upgrades to be commissioned in summer 2009.

SDSS telescope + most systems unchanged.

1000 small-core fibers to replace existing (more objects, less sky contamination).

LBNL CCDs + new gratings improve throughput.

Update electronics + DAQ.
Photometric Redshifts?

- Can we do this without spectroscopy?
- Measuring $H(z)$ requires detection of acoustic oscillation scale along the line of sight.
  - Need $\sim 10$ Mpc accuracy. $n_z \sim 0.003(1+z)$.
- Measuring $D_A(z)$ from transverse clustering requires only 4% in $1+z$.
- Need 10x more sky than spectroscopy. Less robust, but likely feasible.

4% photo-z’s don’t smear the acoustic oscillations.
Distances to Acceleration

![Graph showing the relationship between time and the size of the universe. The graph indicates that the Hubble constant fixes the slope, with present size and time marked. The x-axis represents time relative to the present-day (Gyr), and the y-axis represents the size of the universe. Markings for redshift 0 and redshift 1 are also shown.]
Distances to Acceleration

Hubble constant fixes this slope

Present Size

Decelerating

Redshift 0

Redshift 1

Size of Universe

Time relative to present-day (Gyr)
Distances to Acceleration

Hubble constant fixes this slope

Present Size

Present Time

Redshift 0

Redshift 1

Accelerating Universe has More Lookback Time & Distance

Time relative to present-day (Gyr)

Size of Universe