Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies

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Abstract

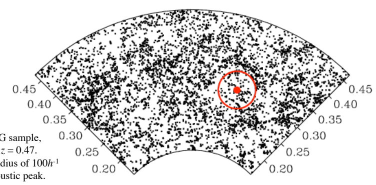
We present the large-scale correlation function measured from a spectroscopic sample of 46,748 luminous red galaxies from the Sloan Digital Sky Survey, covering 3816 square degrees and $0.16 < z < 0.47$. We find a well-detected peak in the correlation function at $100h^{-1}$ Mpc separation that is an excellent match to the predicted shape and location of the imprint of the recombination-epoch acoustic oscillations.

This detection demonstrates the linear growth of structure by gravitational instability between $z = 1000$ at the present and confirms a firm prediction of the standard cosmological theory. The acoustic peak provides a standard ruler by which we can measure the absolute distance to $z = 0.35$ to 5% accuracy and the ratio of the distances to $z = 0.35$ and $z = 1089$ to 4% accuracy. This provides a measurement of cosmological distance and an argument for dark energy based on a geometric method with the same simple physics as the cosmic microwave background (CMB) anisotropies.

From the overall shape of the correlation function, we measure $\Omega_m h^2 = 0.130(n/0.98)^{1.2} \pm 0.011$ (8%). This result is independent from, but agrees with, the value from the anisotropies of the CMB.

We find $\Omega_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\Omega_K$, where w_0 is the dark energy equation of state at $z < 0.35$, but where the constraint is otherwise independent of $w(z)$.

Including the CMB acoustic scale, we find $\Omega_K = -0.010 \pm 0.009$ if the dark energy is a cosmological constant.

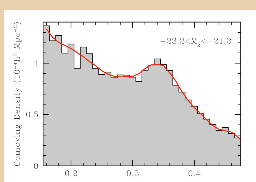


A pie diagram of the LRG sample, running from $z = 0.16$ to $z = 0.47$. The red bullseye has a radius of $100h^{-1}$ Mpc, the scale of the acoustic peak.

The SDSS LRG Sample

The SDSS has two spectroscopic galaxy samples. The Main sample is a flux-limited sample ($r < 17.77$, 90 deg^{-2}) of normal galaxies. The LRG sample uses a color and flux cut to select 15 luminous early-type galaxies per deg^2 out to $z = 0.5$ and down to a flux limit of $r = 19.5$.

In this analysis, we use a spectroscopic sample of 47,000 LRGs over 3816 deg^2 in the redshift range $0.16 < z < 0.47$. The volume surveyed is $0.72h^{-3}$ Gpc^3. The LRG number density of $0.3–1\text{x}10^{-4}h^{-3}$ Mpc^3 is close to optimal for the study of structure on the largest scales.



The comoving number density $n(z)$ of the LRG sample, in units of $10^{-4}h^{-3}$ Mpc^3. The sample is close to constant $n(z)$, i.e. volume-limited, out to z ~ 0.36. The red line is our model of $n(z)$, used to create random catalogs for the correlation analyses.

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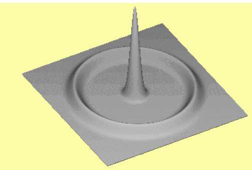
An Acoustic Peak Primer

Before recombination at z~1000, the universe was ionized, and in this plasma the cosmic microwave background photons are well coupled to the baryons and electrons. The photons have such enormous pressure that the sound speed in the plasma is relativistic.

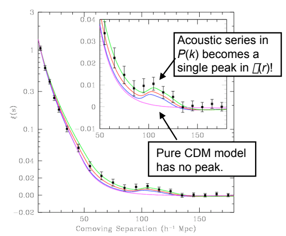
The initial perturbations are equal in the dark matter and baryons. However, an overdensity in the baryons also implies a large overpressure, with the result that a spherical pressure wave is driven into the plasma. By the time of recombination, this wave has reached a comoving radius of 150 Mpc, the sound horizon.

The dark matter overdensity on the other hand remains centrally concentrated. After recombination, perturbations grow gravitationally in response to the sum of the dark matter and baryons. The central concentration dominates, but there is a small (1%) imprint at 150 Mpc scale that generates a single acoustic peak in the matter correlation function.

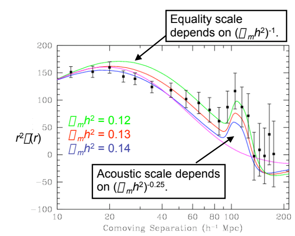


An illustration of the baryonic pressure wave expanding from a central overdensity, where the dark matter perturbation remains. The amplitude of the wave has been exaggerated; it should be only 1% of the central peak. The Universe is a superposition of many such structures.

Importantly, the sound horizon depends only on the baryon-to-photon ratio ($\Omega_b h^2$) to set the sound speed and the matter and radiation densities ($\Omega_m h^2$ and $\Omega_r h^2$) to set the propagation time. Measuring these densities, e.g., from the acoustic peaks of the CMB, allows one to calibrate this standard ruler.



The redshift-space correlation function of LRGs. Note the acoustic peak at $100h^{-1}$ Mpc. The data points are correlated; including this, the best-fit model with $\Omega_b h^2 = 0.024$ has $\chi^2 = 16.1$ with 17 degrees of freedom. The best-fit pure CDM model has $\chi^2 = 27.8$ and is rejected at 3.4σ.



The correlation function times r^2 to flatten out the curve. The acoustic peak is now clearly visible. Three different cosmological models with $\Omega_b h^2 = 0.024$ are shown, along with one pure CDM model. The horizontal scale was computed assuming a particular distance to $z = 0.35$; we introduce this as a parameter in the model fits so as to measure the cosmological distance scale.

We compute the redshift-space correlation function of the LRGs on scales between $10h^{-1}$ and $180h^{-1}$ Mpc. The covariance matrix is derived from 1247 mock catalogs constructed using PTHalos and a model of the halo occupation of LRGs.

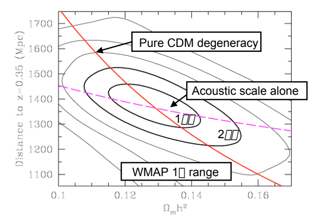
The correlation function reveals a well-detected peak at $100h^{-1}$ Mpc separation. Associating this with the acoustic peak sets the distance to $z = 0.35$, the typical redshift of the sample. More generally, the correlation function is a good fit to models with the baryon density found by WMAP and big bang nucleosynthesis.

From the shape of the correlation function, we can infer the matter density $\Omega_m h^2$, although this is mildly degenerate with the spectral tilt n.

Our best measurement of distance comes from comparing the acoustic scale in the LRG sample to that measured in the CMB. This constrains the distance to $z = 0.35$ to that to $z = 1089$ to be 0.0979 ± 0.0036 (4%). This ratio is highly robust, not only against changes within the standard modeling but also against certain exotic alterations.

With this ratio, we get precise geometric constraints on dark energy and curvature, given in the Table to the right.

Focusing on the local distance scale, we can use our standard ruler to measure Ω_m with only mild effects from $w(z)$ or curvature. We find $\Omega_m = 0.273 + 0.123(1+w_0) + 0.137\Omega_K \pm 0.025$, where w_0 is the dark energy equation of state at $z < 0.35$.



Constraints in the parameter space of $\Omega_m h^2$ and the distance to $z = 0.35$. We have assumed $\Omega_b h^2 = 0.024$ and $n = 0.98$. Changing the tilt alters the value of $\Omega_m h^2$ but does not change the ratio of the distances to $z = 0.35$ and to $z = 1089$ because the acoustic scale is well detected.

	Curved, Λ	Flat, constant w	Flat, Λ
Ω_K	-0.010 ± 0.009	—	—
w	—	-0.80 ± 0.18	—
$\Omega_m h^2$	0.136 ± 0.008	0.135 ± 0.008	0.142 ± 0.005
Ω_m	0.306 ± 0.027	0.326 ± 0.037	0.298 ± 0.025
h	0.669 ± 0.028	0.648 ± 0.045	0.692 ± 0.021
n	0.973 ± 0.030	0.983 ± 0.035	0.963 ± 0.022

Cosmological constraints from a Markov chain analysis combining WMAP and SDSS Main $P(k)$ (Tegmark et al. 2004, PRD, 69, 103501) with the LRG correlation function measurements of the acoustic scale. The improvement is typically a factor of 2.

The Intermediate-Scale Clustering of Luminous Red Galaxies

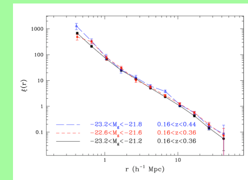
I. Zehavi, D. Eisenstein, R. Nichol, M. Blanton, D. Hogg, et al.

(*Astrophysical Journal*, in press; astro-ph/0411557)

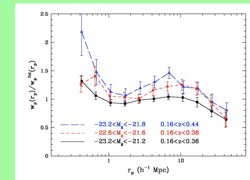
We measure the auto-correlation function of the LRG sample on scales from $300h^{-1}$ kpc to $30h^{-1}$ Mpc. We use projected correlation functions to eliminate the effects of redshift distortions and study three different luminosity subsets.

As expected, luminous red galaxies are highly clustered, with a correlation length of ~$10h^{-1}$ Mpc. We find σ_8=1.80 ± 0.03 for the $-23.2 < M_g < -21.2$ volume-limited subset and a bias of 1.84 ± 0.11 relative to L^* galaxies. The LRG sample shows 4σ evidence for luminosity-dependent bias.

The correlation functions are close to power laws (with slope $r^{-1.9}$) but do show statistically significant deviations. These deviations are similar to those found in the SDSS Main sample. These are naturally explained by contemporary models of galaxy clustering as the transition from intra-halo to inter-halo clustering.



The real-space correlation function of LRGs in three absolute magnitude bins (rest-frame g band, passively evolved to $z = 0.3$). The samples are highly biased, and there is a mild luminosity dependence of the amplitude.



The projected correlation function $w_p(r_p)$ divided by a fiducial $r^{-0.9}$ power-law. The luminosity-dependent bias is now more clear, as is the fact that the correlation functions are not pure power laws (which would be a straight line on this log-log plot).

The Small-Scale Clustering of Luminous Red Galaxies via Cross-Correlation Techniques

D. Eisenstein, M. Blanton, I. Zehavi, et al.

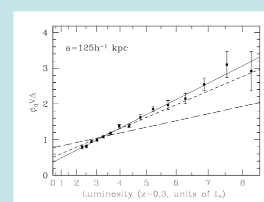
(*Astrophysical Journal*, in press; astro-ph/0411559)

We cross-correlate the spectroscopic LRG sample with a sample of 16 million galaxies from SDSS imaging to probe the clustering around LRGs on scales from $200h^{-1}$ kpc to $7h^{-1}$ Mpc as a detailed function of scale and LRG luminosity. By using a cross-correlation method, we can avoid the shot noise of the sparse LRG sample and obtain very high signal-to-noise ratio results.

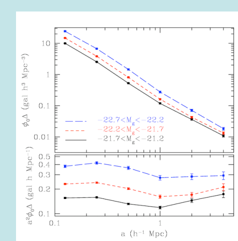
Even with angular methods, the only physical correlations (other than lensing) occur when the two objects are at nearly the same redshift. Therefore, we can use the spectroscopic redshift of the LRG to transform angles into transverse physical distances and the fluxes of the imaging galaxies into luminosities. In particular, we use this property to restrict the imaging sample to a constant passively evolving luminosity cut; in the figures here, we use M^*–0.6 to M^*+1.0.

The cross-correlation is performed using the method of Eisenstein (2003, ApJ, 586, 718) in which weighting as a function of transverse separation is used to synthesize a spherical integral of the real-space cross-correlation function. This has a simple interpretation as the average number of L^* galaxies around the LRG, as weighted by the function $W(r)$. The method has also extremely convenient computational properties.

We find very strong luminosity dependence in the clustering. On $200h^{-1}$ kpc scales, we find a factor of 4 variation in the average number of L^* galaxies around LRGs as one changes the LRG luminosity from $2L^*$ to $8L^*$. However, this luminosity dependence is weaker at larger scales; in other words, galaxy clustering bias is both scale and luminosity dependence. We show that the cross-correlation function is not a power-law in scale, but instead has a dip at 1 Mpc scale relative to smaller and larger scales.



The cross-correlation between LRGs and L^* galaxies as a function of LRG luminosity (in bins of 0.1 mag). The physical scale is about $200h^{-1}$ kpc proper. The horizontal axis has been warped to $L^{1.5}$ as this provides a very nearly linear fit (solid line). The vertical axis is a count of the average number of L^* galaxies near each LRG, weighting the count by a function $W(r)$ [see paper]. There are 4 times more L^* galaxies around LRGs of $8L^*$ than around those of $2L^*$. The short and long dashed lines show the fits for $1.6h^{-1}$ and $7h^{-1}$ Mpc, respectively. There is clear evidence that the luminosity dependence is also scale dependent.



The cross-correlation between LRGs and L* galaxies as a function of scale. Three different LRG luminosity bins are shown (M_g* is -20.35). The bottom panel shows the results divided by a r^{-2} power-law. The luminosity dependence in the results is obvious, as is the deviation from a pure power-law.