THREE-DIMENSIONAL GENUS TOPOLOGY OF LUMINOUS RED GALAXIES

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ABSTRACT

We measure the three-dimensional genus topology of large-scale structure using luminous red galaxies (LRGs) in the Sloan Digital Sky Survey and find it consistent with the Gaussian random phase initial conditions expected from the simplest scenarios of inflation. This studies three-dimensional topology on the largest scales ever obtained. The topology is spongelike. We measure topology in two volume-limited samples: a dense shallow sample studied with smoothing length of 21 h⁻¹ Mpc, and a sparse deep sample studied with a smoothing length of 34 h⁻¹ Mpc. The amplitude of the genus curve is measured with 4% uncertainty. Small distortions in the genus curve expected from nonlinear biasing and gravitational effects are well explained (to about 1σ accuracy) by N-body simulations using a subhalo-finding technique to locate LRGs. This suggests that the formation of LRGs is a clean problem that can be modeled well without any free-fitting parameters. This bodes well for using LRGs to measure the characteristic scales such as the baryon oscillation scale in future deep redshift surveys.

Key words: cosmology: observations – large scale structure of universe – methods: numerical

1. INTRODUCTION

Topology of large-scale structure in the universe has been studied over the years through analyses of large-scale distribution of galaxies in three dimensions. The genus statistic was used to characterize the topology (Gott et al. 1986, 1987, 1989; Hamilton et al. 1986; Vogeley et al. 1994; Park et al. 2005a, 2005b). Measuring the genus as a function of density (Gott et al. 1986, 1987) allows us to compare the topology observed with that expected for Gaussian random phase initial conditions, as predicted in a standard big bang inflationary model (Guth 1981; Linde 1983) where structure originates from random quantum fluctuations in the early universe.

At large scales where fluctuations are still in the linear regime, growing in place without changing topology, topology at the median density level is expected to be spongelike (Gott et al. 1986, 1987). Small deviations from the random phase curve give important information about biased galaxy formation and nonlinear gravitational clustering as shown by perturbation theories and large N-body simulations (Matsubara 1994; Park et al. 2005a). Previous models of galaxy clustering suggested either a meatball topology, isolated clusters growing in a low-density connected background (Press & Schechter 1974; Soneira & Peebles 1978), or a Swiss cheese topology, isolated voids surrounded on all sides by walls (Einasto et al. 1980). But studies of many observational samples have shown in every case a spongelike median density contour as expected from inflation (Gott et al. 1986, 1989, 2008; Moore et al. 1992; Vogeley et al. 1994; Canaveses et al. 1998; Hikage et al. 2002, 2003; Park et al. 2005b).

We have previously measured the three-dimensional topology of the nearby Main galaxies (Strauss et al. 2002) of the Sloan Digital Sky Survey (SDSS; York et al. 2000; Stoughton et al. 2002; Gunn et al. 2006) data at smoothing lengths ranging from 3.5 to 11 h⁻¹ Mpc (see Park et al. 2005b for details). The overall agreement with the best-fit Gaussian random phase genus curve and the mock surveys in a Λ cold dark matter (ΛCDM) is remarkable, strongly supporting the predictions of inflation.

Small deviations from the Gaussian random phase distribution are expected because of nonlinear gravitational evolution and biased galaxy formation, and these can now be observed with sufficient accuracy to do model testing of galaxy formation scenarios. In this Letter, we will analyze the three-dimensional distribution of the luminous red galaxies (LRGs; Eisenstein et al. 2001) observed by the SDSS to study the genus topology at very large scales. The results will be compared with those from the nearby galaxies and with those from N-body simulations of the inflation-based ΛCDM universe.

2. LUMINOUS RED GALAXIES

The LRGs in the SDSS have already proven useful in refining cosmological parameters (Tegmark et al. 2006). Measuring the genus topology of the LRGs is of particular importance because it allows us to observe topology on the largest scales, and because the LRGs are expected to play an important role in characterizing dark energy, i.e., through the ratio of dark energy pressure to energy density (see Bassett et al. 2005; Eisenstein et al. 2005; Percival et al. 2007 for a review).

We use the LRG sample from the SDSS. The sky coverage of the sample is similar to that of SDSS Data Release 5 (Adelman-McCarthy et al. 2006). The angular selection function is based on the spherical polygon description of LSS-DR4plus catalog (Blanton et al. 2003, 2005). To maximize the volume-to-surface ratio, we trim the DR4plus sample (see Figure 1 and the text of Park et al. 2007). These cuts leave 68,203 LRGs over about 4464 deg² in the survey region.

We constructed two volume-limited subsamples of LRGs in passively evolved luminosity and redshift ranges. The subsamples are \(-21.2 < M_{\text{g,0.3}} < -23.2\) with \(0.2 < z < 0.36\), and \(-21.8 < M_{\text{g,0.3}} < -23.2\) with \(0.2 < z < 0.44\), where we have applied k-corrections and passively evolved the galaxies to a fiducial redshift of 0.3. We label them “SHALLOW” and “DEEP,” respectively. Both subsamples are selected to reduce the artifacts caused by the LRG selection cuts. The resulting comoving number density of LRGs are approximately constant (see Zehavi et al. 2005 for details). The sample DEEP...
Figure 1. Distribution of LRGs of the SDSS. Solid boundary lines define the SHALLOW sample, and the dashed lines define the DEEP sample.

(SHALLOW) contains 32,067 (14,968) galaxies. The absolute magnitude and redshift limits of these samples are illustrated in Figure 1 (see also Table 1). We will measure the genus topology magnitude and redshift limits of these samples are illustrated in (SHALLOW) contains 32,067 (14,968) galaxies. The absolute magnitude and redshift limits of these samples are illustrated in Figure 1 (see also Table 1). We will measure the genus topology of the DEEP (SHALLOW) sample with a smoothing length of 21(34)h⁻¹ Mpc. The smoothing lengths chosen are large enough to avoid unwanted shot noise effects (see Gott et al. 1986).

3. N-BODY SIMULATION

We completed a 2048³ particle 4915.2h⁻¹ Mpc size CDM simulation adopting the Wilkinson Microwave Anisotropy Probe (WMAP) three-year parameters (Spergel et al. 2007): \( \Omega_m = 0.238, \Omega_\Lambda = 0.762, \Omega_b = 0.042, n_s = 0.958, \sigma_8 = 0.761, \) and \( h = 0.732, \) where \( \Omega_m, \Omega_\Lambda, \) and \( \Omega_b \) are the density parameters due to matter, cosmological constant, and baryon, respectively, \( n_s \) is the slope of the power spectrum at large scales, and \( \sigma_8 \) is the rms density fluctuation at 8h⁻¹ Mpc scale. The simulation is run by a PM+Tree N-body code (Dubinski et al. 2004) and has a force resolution of 0.24 h⁻¹ Mpc.

We identify the most massive dark matter subhalos as LRGs. The subhalos are the gravitationally bound halos not subject to tidal disruption (Kim & Park 2006), and having more than 30 member particles. To compare with the observational data, we saved the particle positions and velocities along the past light cone of 12 well-separated observers who are making mock SDSS DR4plus LRG surveys. The subhalos are found on the past light cone surface. The minimum halo masses matching the observed number densities of the SHALLOW and DEEP LRG samples are found as a function of redshift and applied to the subhalos data on the past line cone when mock surveys are made. In each mock survey, we pick the most massive subhalos when the mean number density of the LRGs is matched. At small nonlinear scales, the genus depends sensitively on the method by which galaxies are identified within the simulation. Park et al. (2005a) and Gott et al. (2008) have extensive studies on this question.

4. THE GENUS AND RELATED STATISTICS

To measure the genus, we smooth the LRG number density distribution with a Gaussian smoothing ball of radius \( R_G. \) To remove the small radial variation of LRG number density in our samples, we divide the density by the radial selection function in the Appendix of Zehavi et al. (2005). Then the isodensity contour surfaces of the smoothed galaxy density distribution are searched to calculate the genus. The contour surfaces are labeled by \( \nu, \) which is related with the volume fraction \( f \) on the high-density side of the density contour surface by

\[
 f = \frac{1}{\sqrt{2\pi}} \int_0^\infty e^{-x^2/2} \, dx.
\]

The \( f = 50\% \) contour corresponds to the median volume fraction contour \( (\nu = 0). \) For Gaussian random phase initial conditions, the genus curve is

\[
 g(\nu) = A(1 - \nu^2) e^{-\nu^2/2},
\]

where the amplitude \( A = ((k^2/3)^{3/2}/2\pi^2 \) and \( k^2 \) is the average value of \( k^2 \) in the smooth power spectrum (Hamilton et al. 1986; Doroshkevich 1970)

The shape of the genus curve can be parameterized by several variables. First, there is the amplitude of the genus curve as measured by fitting the amplitude of the best-fitting Gaussian random phase curve from Equation (2). This gives information about the power spectrum and phase correlation of the density fluctuation. Deviations of the genus curve from the theoretical random phase case can be quantified by the following three variables:

\[
 \Delta \nu = \int_{-1}^{1} \frac{g(\nu)}{\Delta \nu} d\nu, \quad A_\nu = \int_{-2}^{2} \frac{g(\nu)}{\Delta \nu} d\nu, \quad A_C = \int_{-2}^{2} \frac{g(\nu)}{A_\nu} d\nu,
\]

where \( g(\nu) \) is the genus of the best-fit random phase curve (Equation 2). Thus, \( \Delta \nu \) measures any shift in the central portion of the genus curve. The Gaussian curve (Equation 2) has \( \Delta \nu = 0. \) A negative value of \( \Delta \nu \) is called a “meatball shift” caused by a greater prominence of isolated connected high-density structures which push the genus curve to the left. \( A_\nu \) (\( A_C \)) measure the observed number of voids (clusters) relative to those expected from the best-fitting Gaussian curve.
5. RESULTS

We have measured the three-dimensional genus topology of the LRGs in the SHALLOW and DEEP samples with the smoothing lengths described above. The genus curves are shown in Figure 2. The maximum value of the genus curve reaches about 170, and the amplitude is measured with only 4% error at $21h^{-1}$ Mpc scale. This compares with the previously smallest error of 9.4% at $5h^{-1}$ Mpc scale for the genus obtained from the Main Galaxy Sample of the SDSS (Park et al. 2005b). The data for each sample are shown as the jagged line. Each genus curve is compared with the best-fit Gaussian random phase curve from Equation (2) (smooth solid lines). The observational data agree well with the Gaussian curves, but there are small differences between them due to the nonlinear biasing and gravitational effects (Park et al. 2005a).

The dashed lines show the mean of 12 mock SDSS Surveys constructed from our 2048$^3$ particle simulation. Although our two volume-limited samples contain galaxies typically with different absolute magnitude and redshift, the genus curves measured from them show a very good overall agreement. Moreover, there is a remarkable agreement between observations and the mock surveys. The number of voids (the depth of the valley at $\nu<1$) is less than the number of clusters (the depth of the valley at $\nu>1$). The phenomenon that clusters outnumber voids is reproduced by the simulations extremely well. The amplitude of the genus curve agrees well between observations and simulations, showing that the nonlinear power spectrum and degree of phase correlation of the LRG distribution smoothed at $RG=21h^{-1}$ Mpc and $34h^{-1}$ Mpc are also modeled well.

The small deviations of the genus curves from the Gaussian cases are quantified by our distortion parameters $\Delta \nu$, $AV$, and $AC$. These statistics for the observed LRG distribution are within approximately 1σ of those expected from the 12 mock surveys as shown in Figures 3 and 4 and are summarized in Table 1.

In Figure 3, the predictions for random phase curve (Equation (2)) are shown by stars with three and five legs for the cosmological parameters estimated from WMAP three-year (Spergel et al. 2007) and five-year maps only (Dunkley et al. 2009), respectively. In Figure 4, the random phase curve is indicated by a point where $AV=1$ and $AC=1$. The mock catalogs are indicated by open circles. The observational data are indicated by filled circles with 1σ error bars showing the 1σ variation from one mock survey to the other mock survey. Importantly, there is no free-fitting parameter here for any of these quantities. So it is noteworthy that in $A$, $\Delta \nu$, $AV$, and $AC$ the data are within about 1σ of the predicted values. The statistic showing the maximum difference between observation and simulation is $AV$; the observed voids are somewhat larger and fewer relative to those found in mock SDSS LRG surveys.
This suggests that finding the objects corresponding to LRGs is a relatively clean problem. Our genus topology study shows that N-body simulation together with identification of LRGs with the most massive dark subhalos can produce robust results in very good agreement with the observational data. Our results here show that the $\Lambda$CDM model we adopted in the N-body simulation is a close approximation of the real universe. The results also suggest that it will be possible to model well the formation of LRGs in the future Sloan III Survey by using large N-body simulations to check and correct for any small systematic effects due to nonlinear gravitational effects and biasing without needing free-fitting parameters.

6. CONCLUSIONS

We measured the three-dimensional genus topology of large-scale structure using the LRG galaxies in the Sloan Survey. The amplitude of the genus curve is now measured within about 4% error at 21 $h^{-1}$ Mpc smoothing scale. The results are consistent with the predictions of the $\Lambda$CDM model with WMAP cosmological parameters, and with Gaussian random phase initial conditions expected from standard inflation. The topology is spongelike. Small distortions from the random phase curve expected from nonlinear gravitational effects and biasing are observed. These are modeled well (at the 1$\sigma$ level) by N-body simulations that pick the largest gravitationally bound halos not subject to tidal disruption as the sites for LRG galaxies to form. The data on topology, including the number of voids and clusters, the location of the peak in the genus curve, and its amplitude are all fit well without any free-fitting parameters. Thus, the formation of LRGs appears to be a relatively clean problem that can be modeled well using CDM and gravity alone, and this bodes well for using N-body simulations to calibrate the measurement of baryon oscillations using LRGs.

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REFERENCES

Adelman-McCarthy, J. K., et al. 2006, ApJS, 162, 38
Bassett, B. A., Nichol, B., Eisenstein, D. J., & WFMOS Feasibility Study Dark Energy Team, 2005, Astron. Geophys., 42, 26
Blanton, M. R., Lin, H., Lupton, R. H., Maley, F. M., Young, N., Zehavi, I., & Loveday, J. 2003, AJ, 125, 2276
Blanton, M. R., et al. 2005, ApJ, 129, 2562
Canaveses, A., et al. 1998, MNRAS, 297, 777
Doroshkevich, G. 1970, Astrofizika, 6, 320
Dubinski, J., Kim, J., Park, C., & Humble, R. 2004, New A., 9, 111
Dunkley, K., et al. 2009, ApJS, 180, 306
Einasto, J., Joueever, M., & Saar, E. 1980, MNRAS, 193, 353
Eisenstein, D. J., et al. 2001, AJ, 122, 2267
Eisenstein, D. J., et al. 2005, ApJ, 633, 560
Gott, J. R., Melott, A. L., & Dickinson, M. 1986, ApJ, 306, 341
Gott, J. R., Weinberg, D. N., & Melott, A. L. 1987, ApJ, 319, 1
Gott, J. R., et al. 1989, ApJ, 122, 2276
Hikage, C., et al. (The SDSS Collaboration) 2002, PASJ, 54, 707
Hikage, C., et al. 2003, PASJ, 55, 911
Kim, J., & Park, C. 2006, ApJ, 639, 600
Linde, A. D. 1983, Phys. Lett. B, 129, 177
Matsubara, T. 1994, ApJ, 434, L43
Moore, B., et al. 1992, MNRAS, 256, 477
Park, C., Choi, Y.-Y., Vogeley, M. S., Gott, J. R., & Blanton, M. R. 2007, ApJ, 658, 898
Park, C., Kim, J., & Gott, J. R. 2005a, ApJ, 633, 1
Park, C., et al. (The SDSS Collaboration) 2005b, ApJ, 633, 11
Percival, W. J., Cole, S., Eisenstein, D. J., Nichol, R. C., Peacock, J. A., Pope, A. C., & Szalay, A. S. 2007, MNRAS, 381, 1053
Press, W. H., & Schechter, P. 1974, ApJ, 187, 425
Soneira, R. M., & Peebles, P. J. E. 1978, ApJ, 83, 845
Spergel, D. N., et al. 2007, ApJS, 170, 377
Stoughton, C., et al. 2002, AJ, 123, 485
Strauss, M. A., et al. 2002, AJ, 124, 1810
Tegmark, M., et al. 2006, Phys. Rev. D, 74, 123507
Vogeley, M. S., Park, C., Geller, M. J., Huchra, J. P., & Gott, J. R. 1994, ApJ, 420, 525
York, D. G., et al. 2000, AJ, 120, 1579
Zehavi, I., et al. 2005, ApJ, 621, 22