CLUSTERING OF DARK MATTER HALOS ON THE LIGHT CONE: SCALE, TIME, AND MASS DEPENDENCE OF THE HALO BIASING IN THE HUBBLE VOLUME SIMULATIONS

TAKASHI HAMANA,1,2 NAOKI YOSHDIA,2 YASUSHI SUTO,3 AND AUGUST E. EVRARD4

Received 2001 July 11; accepted 2001 October 1; published 2001 October 25

ABSTRACT

We develop a phenomenological model to predict the clustering of dark matter halos on the light cone by combining several existing theoretical models. Assuming that the velocity field of halos on large scales is approximated by linear theory, we propose an empirical prescription of a scale, mass, and time dependence of halo biasing. We test our model against the Hubble volume N-body simulation and examine its validity and limitations. We find a good agreement in two-point correlation functions of dark matter halos between the phenomenological model predictions and measurements from the simulation for $R > 5 h^{-1} \text{Mpc}$ in both the real and redshift spaces. Although calibrated on the mass scale of groups and clusters and for redshifts of up to $z \sim 2$, the model is quite general and can be applied to a wider range of astrophysical objects, such as galaxies and quasars, if the relation between dark halos and visible objects is specified.

Subject headings: cosmology: theory — dark matter — galaxies: halos — large-scale structure of universe — methods: numerical

1. INTRODUCTION

Clustering properties of luminous objects such as galaxies, clusters of galaxies, and quasars are useful tools not only in studying the nature of those objects but also in probing the cosmology. Current popular models predict that the cosmic structures evolved by gravitational instability from primordial fluctuations of mass density field generated through an inflationary epoch. The strongest support for this picture comes from recent detections of multiple peaks in the angular power spectrum of the cosmic microwave background radiation by the BOOMERANG (Netterfield et al. 2001) and MAXIMA-1 (Lee et al. 2001) experiments. On the other hand, our knowledge about cosmic structures after the last scattering epoch, especially at high redshifts of $z > 1$, is relatively poor, mostly because of observational costs associated with mapping the structure of many distant faint objects. Thanks to recent developments in instrument technology, this situation is improving dramatically. Large flows of data from the ongoing wide-field galaxy and quasar redshift surveys, e.g., the Two-degree Field spectrograph and the Sloan Digital Sky Survey, promise a new era of precision cosmology.

How accurately can we understand the nature of the clustering of objects that will be precisely measured by these ongoing surveys? To construct a theoretical model of clustering of visible objects (galaxy, cluster of galaxies, and quasars) is not simple because it requires a detailed understanding of the biasing relation between those objects and the distribution of underlying dark mass. Popular models of the biasing based on the peak (Kaiser 1984; Bardeen et al. 1986) or the Press-Schechter theory (Mo & White 1996) are successful in capturing some essential features of biasing (Jing & Suto 1998). None of the existing models of bias, however, seem to be sophisticated enough for the coming precision cosmology era. Development of a more detailed theoretical model of bias is needed.

One way to understand the clustering of objects is to describe it in terms of dark matter halos. The standard picture of structure formation predicts that the luminous objects form in a gravitational potential of dark matter halos. Therefore, a detailed description of halo clustering is the most basic step toward understanding the clustering of those objects. Eventually the halo model can be combined with the relation between the halos and luminous objects that has been separately investigated numerically and/or (semi) analytically, e.g., by Kauffmann & Haehnelt (2000).

The purpose of this Letter is to improve theoretical predictions for clustering of luminous objects in large observational catalogs by developing a theoretical model of clustering of dark matter halos expected along the past light cone of an observer. Special attention is paid to the scale, time, and mass dependence of halo biasing. To do this, we combine several existing theoretical models, including nonlinear gravitational evolution, the peculiar velocities of halos, and halo biasing. We also include the light cone effect, which is crucial when one analyzes data distributed over a broad redshift range. We then test the resulting predictions directly against a light cone output from large N-body simulations. This work presents a natural generalization of our previous paper (Hamana, Colombi, & Suto 2001) discussing the clustering of dark matter on the light cone. Nevertheless, this line of research benefits greatly from the modeling of huge spatial volumes in simulations, a situation that has become possible only recently.

2. LIGHT CONE OUTPUT AND SNAPSHOT DATA FROM THE HUBBLE VOLUME SIMULATION

In the following analysis, we use both “light cone output” and snapshot data produced from the Hubble volume Λ cold dark matter (CDM) simulation (Evrard et al. 2001). The initial CDM power spectrum is computed by CMBFAST (Seljak & Zaldarriaga 1996) assuming that $\Omega_\text{M} = 0.04$ and $\Omega_\text{CDM} = 0.26$ and is normalized so that $\sigma_8 = 0.9$. The background cosmology is spatially flat with matter density $\Omega_\text{m} = \Omega_\text{CDM} + \Omega_\text{b} = 0.3$, cosm-
logical constant $\Omega_0 = 0.7$, and Hubble constant $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. The simulation employs $N = 10^9$ dark matter particles in a box of length 3000 h$^{-1}$ Mpc on a side. The mass per particle is $2.25 \times 10^{12}$ h$^{-1}$ $M_{\odot}$. The light cone output is generated in the following manner: We locate a fiducial observer at a corner of the simulation box at $z = 0$. The position and velocity of each particle are recorded whenever it crosses the past light cone of this observer, and these coordinates are accumulated in a single data file. We use the “deep wedge” output, which subtends a 81.45 deg$^2$ field directed along a diagonal of the simulation box up to $z = 4.4$. These data automatically include the evolution of clustering with look-back time (distance from the observer), which is essential in comparing models and observations of objects distributed over a broad range of redshifts.

We identify dark matter halos on the light cone using the standard friends-of-friends algorithm with a linking parameter of $b = 0.164$ (in units of the mean particle separation). Jenkins et al. (2001) show that such an algorithm produces a set of clusters whose mass function is well fitted by a single functional form. We set the minimum mass of the halos as $2.2 \times 10^{13}$ h$^{-1}$ $M_{\odot}$, which consists of 10 simulation particles.

We find that the Press-Schechter model (Press & Schechter 1974) underpredicts the cumulative mass function of our halos with $M > 2.2 \times 10^{13}$ h$^{-1}$ $M_{\odot}$, at $z > 1$, while Sheth & Tormen (1999, hereafter ST99) overpredict beyond $z \sim 1.5$. This tendency is consistent with the previous finding of Jenkins et al. (2001) that ST99 overestimate the number of halos when $\ln a^{-1}$ becomes large.

In § 3.2 we also use the halo catalog identified in the $z = 0$ snapshot data of the Hubble volume simulation to study the mass and scale dependence of halo biasing in detail. The halos are identified in the same manner as described above except that the minimum halo mass is $6.8 \times 10^{13}$ h$^{-1}$ $M_{\odot}$ (30 simulation particles). The total number of identified halos in the $(3000 h^{-1}$ Mpc)$^3$ cube is 1,560,995. We note that the mass function and clustering of this halo catalog at $z = 0$ were already studied by Jenkins et al. (2001) and Colberg et al. (2000), respectively. Our analysis below aims at a detailed modeling of the halo bias properties at $z = 0$ in order to calibrate the empirical halo bias model on the light cone.

3. STATISTICS OF HALOS ON THE LIGHT CONE

3.1. Theoretical Predictions of Two-Point Correlation Functions on the Light Cone

As emphasized by Suto et al. (1999), for instance, observations of high-redshift objects are carried out only through the past light cone defined at $z = 0$, and the corresponding theoretical modeling should properly take account of relevant physical effects. Those include (1) nonlinear gravitational evolution, (2) linear and nonlinear redshift space distortion, (3) selection function of the target objects, and (4) scale-, mass-, and time-dependent biasing of those objects. In the present section we describe a model for the two-point statistics for dark matter halos with all the above effects properly considered. In what follows, we briefly describe the outline of our modeling (see Hamana et al. 2001 for details), focusing on those issues specific to dark matter halos.

Gravitational evolution of mass fluctuations can be accurately modeled by adopting a fitting formula of Peacock & Dodds (1996) for the nonlinear power spectrum in real space, $P_R^H(k, z)$. Then, the nonlinear power spectrum in redshift space is given as (Kaiser 1987; Peacock & Dodds 1996)

$$P^S(k, \mu, z) = P_R^H(k, z)(1 + \beta_{halo} \mu^2)D_{rel}(k\mu \sigma_{halo}),$$

where $\mu$ is the direction cosine in k-space, $\sigma_{halo}$ is the one-dimensional pairwise velocity dispersion of halos, and $\beta_{halo} = f(z)/b_{halo}$. In the above expression, $f(z)$ is the logarithmic derivative of the linear growth rate $D(z)$ with respect to the scale factor, and $b_{halo}$ is the halo bias factor. While both $\sigma_{halo}$ and $b_{halo}$ depend on the halo mass $M$, separation $R$, and $z$ in reality, we neglect their scale dependence in computing the redshift distortion and adopt the halo number-weighted averages:

$$\sigma^2_{halo}(> M, z) \equiv \frac{\int_0^M 2D^2(z)\sigma^2(M, z = 0) n_j(M, z)dM}{\int_0^M n_j(M, z)dM},$$

$$b_{halo}(> M, z) \equiv \frac{\int_0^M b_{proj}(M) n_j(M, z)dM}{\int_0^M n_j(M, z)dM},$$

where we adopt the halo mass function $n_j(M, z)$ fitted by Jenkins et al. (2001) and the mass-dependent halo bias factor $b_{proj}(M)$ proposed by ST99. The value of $\sigma(M, z = 0)$, the halo center-of-mass velocity dispersion at $z = 0$, is modeled following Yoshida, Sheth, & Diaferio (2001):

$$\sigma(M, z = 0) = \frac{430/\sqrt{3}}{1 + (M/2.487 \times 10^{10} h^{-1} M_{\odot})^{0.284}} \text{ km s}^{-1}.$$
shown in filled triangles and open circles, respectively. For $R > 2R_{\text{vir}}(M, z)$ and otherwise 0, where $R_{\text{vir}}(M, z)$ is the virial radius of the halo of mass $M$ at $z$ and $\alpha_y(R, z)$ is the mass variance smoothed over the top-hat radius $R$. While the above cutoff below $2R_{\text{vir}}(M, z)$ is intended to simply incorporate the halo exclusion effect very roughly, we find it a reasonable approximation, as shown below.

We test this empirical bias model against the halo catalog generated from the snapshot data at $z = 0$. To do this, we compute the two-point correlation functions of halos of mass $M_{\text{halo}} > M_{\text{min}}$ in real space, then we divide them directly by the corresponding mass correlation function. We adopt the estimator $\xi = (DD - 2DR + RR)/RR$ (Landy & Szalay 1993) with the standard bootstrap method with 200 random resamplings. Figure 1 compares the resulting bias factor of halos, $b_{\text{halo}}(M, z)$, open circles, crosses, and filled triangles are for $M_{\text{min}} = 4.1 \times 10^{14}, 2.0 \times 10^{14}$, and $6.8 \times 10^{13}$ $h^{-1} M_\odot$, respectively. The horizontal dotted lines indicate the $b_{\text{ST}}(M, z)$, and our model predictions (eq. [5]) are plotted in solid lines. Given the simple formula that we adopt, the agreement with the numerical simulations at $z = 0$ is satisfactory.

Then, our empirical halo bias model can be applied to the two-point correlation function of halos at $z$ in redshift space as

$$b_{\text{halo}}(M, R, z) = b_{\text{halo}}(M, z)^{1.0 + b_{\text{ST}}(M, z)\alpha_y(R, z)}$$

for $R > 2R_{\text{vir}}(M, z)$ and otherwise 0, where $R_{\text{vir}}(M, z)$ is the comoving volume element between the survey range $z_{\text{min}} < z < z_{\text{max}}$ (Matarrese et al. 1998; Moscardini et al. 1998; Yamamoto & Suto 1999; Suto et al. 2000):

$$\xi_{\text{halo}}(M, R, z) = b_{\text{halo}}^2(M, R, z) \int_0^\infty P^2(k, z) \frac{\sin kR \Delta^2 dk}{kR} \frac{2}{\pi^2}.$$  

Finally, the correlation function of halos on the light cone is computed by averaging over the appropriate halo number density and the comoving volume element between the survey range $z_{\text{min}} < z < z_{\text{max}}$ (Matarrese et al. 1998; Moscardini et al. 1998; Yamamoto & Suto 1999; Suto et al. 2000):

$$\xi_{\text{halo}}^{1/2}(> M, R) = \frac{\int_0^\infty dM \int_{z_{\text{min}}}^{z_{\text{max}}} dz (dV/dz)n_j^2(M, z)\xi_{\text{halo}}(M, R, z)}{\int_0^\infty dM \int_{z_{\text{min}}}^{z_{\text{max}}} dz (dV/dz)n_j^2(M, z)}.$$  

where $dV/dz$ is the comoving volume element per unit solid angle (Hamana et al. 2001). Although our modeling is not completely self-consistent in the sense that the scale dependence of the halo bias factor is neglected in describing the redshift distortion (§ 3.2), the above prescription is supposed to provide a good approximation since the scale dependence in the biasing is of secondary importance in the redshift distortion effect of halos.

3.3. Clustering on the Light Cone

The two-point correlation functions on the light cone are plotted in Figure 2 for halos with $M > 5.0 \times 10^{13}$ and $2.2 \times 10^{13}$ $h^{-1} M_\odot$ and dark matter from top to bottom. The range of redshifts is $0 < z < 1$ (left panel) and $0.5 < z < 2$ (right panel). Predictions in redshift and real spaces are plotted in dashed and solid lines, while simulation data in redshift and real spaces are shown in filled triangles and open circles, respectively.

Our model and simulation data also show quite good agreement for dark halos at scales larger than $5 h^{-1}$ Mpc. Below that scale, they start to deviate slightly in a complicated fashion depending on the halo mass and redshift range. This discrepancy may be ascribed to both the numerical limitations of the current simulations and our rather simplified model for the halo biasing (eq. [5]). Nevertheless, the clustering of clusters on scales below $5 h^{-1}$ Mpc is difficult to determine observationally anyway, and our model predictions differ from the simulation data by only $\sim 20\%$ at most. Therefore, we conclude that in practice our empirical model provides a successful description of halo clustering on the light cone.

4. CONCLUSIONS AND DISCUSSION

We develop a phenomenological model to predict the clustering of dark matter halos on the light cone by combining several existing theoretical models. Combining the TS00 bias model with the ST99 mass function model, we are, for the first time, able to construct a halo bias model that reproduces well the mass and radial dependence measured in the Hubble volume simulation output data. Once calibrated with the $z = 0$ snapshot data, we find that our model agrees well with the two-point correlation functions of the simulated halos up to $z = 2$ in both real and redshift spaces. Although we show that this phenomenological model of halo clustering provides accurate predictions for the two-point correlation function of halos over a limited range in mass and redshift, we anticipate that it can be applied to a wider range of scales. This opens up application to modeling observations of various astrophysical objects, such as galaxies, clusters of galaxies, and quasars, under model-specific assumptions for the relation between dark halos and luminous objects.

T. H. thanks G. Börner and M. Bartelmann for the hospitality.
during his stay at MPA, where most of the present work was performed. He also acknowledges support from Research Fellowships of the Japan Society for the Promotion of Science. The simulation used here was carried out by the Virgo Consortium.\textsuperscript{6}

\textsuperscript{6} The light cone data are publicly available at http://www.mpa-garching.mpg.de/Virgo.


during his stay at MPA, where most of the present work was performed. He also acknowledges support from Research Fellowships of the Japan Society for the Promotion of Science. The simulation used here was carried out by the Virgo Consortium.\textsuperscript{6}

\textsuperscript{6} The light cone data are publicly available at http://www.mpa-garching.mpg.de/Virgo.

This research was supported in part by the grant-in-aid from the Ministry of Education, Science, Sports, and Culture of Japan (07CE2002, 12640231). A. E. E. acknowledges support from NSF grant AST 98-03199, NASA grant NAG 5-7108, and the Scientific Visitor Program of the Carnegie Observatories in Pasadena.

**REFERENCES**

Bardeen, J. M., Bond, J. R., Kaiser, N., & Szalay, A. S. 1986, ApJ, 304, 15

Colberg, J. M., et al. 2000, MNRAS, 319, 209

Evrard, A. E., et al. 2001, ApJ, submitted

Hamana, T., Colombi, S., & Suto, Y. 2001, A&A, 367, 18

Jenkins, A., et al. 2001, MNRAS, 321, 372

Jing, Y. P. 1998, ApJ, 503, L9

Jing, Y. P., & Suto, Y. 1998, ApJ, 494, L5

Kaiser, N. 1984, ApJ, 284, L9

———. 1987, MNRAS, 227, 1

Kauffmann, G., & Haehnelt, M. 2000, MNRAS, 311, 576

Lacey, C., & Cole, S. 1993, MNRAS, 262, 627

Landy, S. D., & Szalay, A. S. 1993, ApJ, 412, 64

Lee, A. T., et al. 2001, ApJ, 561, L1

Magira, H., Jing, Y. P., & Suto, Y. 2000, ApJ, 528, 30

Matarrese, S., Coles, P., Lucchin, F., & Matarrese, S. 1998, MNRAS, 285, 115

Mo, H. J., & White, S. D. M 1996, MNRAS, 282, 347

Moscardini, L., Coles, P., Lucchin, F., & Matarrese, S. 1998, MNRAS, 299, 95

Netterfield, C. B., et al. 2001, ApJ, submitted (astro-ph/0104460)

Peacock, J. A., & Dodds, S. J. 1996, MNRAS, 280, L19

Press, W. H., & Schechter, P. 1974, ApJ, 187, 425

Seljak, U., & Zaldarriaga, M. 1996, ApJ, 469, 437

Sheth, R. K., & Diaferio, A. 2001, MNRAS, 322, 901

Sheth, R. K., & Tormen, G. 1999, MNRAS, 308, 119 (ST99)

Suto, Y., Magira, H., Jing, Y. P., Matsubara, T., & Yamamoto, K. 1999, Prog. Theor. Phys. Suppl., 133, 183

Suto, Y., Yamamoto, K., Kitayama, T., & Jing, Y. P. 2000, ApJ, 534, 551

Tanaya, A., & Suto, Y. 2000, ApJ, 542, 559 (TS00)

Ueda, H., Inoh, M., & Suto, Y. 1993, ApJ, 408, 3

Yamamoto, K., & Suto, Y. 1999, ApJ, 517, 1

Yoshida, N., Sheth, R., & Diaferio, A. 2001, MNRAS, 325, 803

Yoshikawa, K., Tanuya, A., Jing, Y. P., & Suto, Y. 2001, ApJ, 558, 520