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GALAXY CORRELATION IN A BUBBLY UNIVERSE

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ABSTRACT

Recent redshift surveys suggest that most galaxies may be distributed on the surfaces of bubbles surrounding large voids. To investigate the quantitative consistency of this qualitative picture of large-scale structure, we study analytically the clustering properties of galaxies in a universe filled with spherical shells. In this paper, we report the results of the calculations for the spatial and angular two-point correlation functions of galaxies. With $\sim 20\%$ of galaxies in clusters and a power law distribution of shell sizes, $n_{sh}(R) \sim R^{-\alpha}$, $\alpha \simeq 4$, the observed slope and amplitude of the spatial two-point correlation function $\xi_{gg}(r)$ can be reproduced. (It has been shown that the same model parameters reproduce the enhanced *cluster* two-point correlation function, $\xi_{cc}(r)$.) The corresponding angular two-point correlation function $w(\theta)$ is calculated using the relativistic form of Limber's equation and the Schecter-type luminosity function. The calculated $w(\theta)$ agrees with the observed one quite well on small separations ($\theta \lesssim 2$deg).

I. INTRODUCTION

How are galaxies distributed in space on large scales? Although the observational data base in cosmology has improved dramatically in recent years, we still have only a partial understanding of this issue. Beginning in the late seventies and especially with the first results of the CfA2 redshift survey extension (de Lapparent, Geller, and Huchra 1986), a picture has emerged in which a large fraction of galaxies appear to be distributed on the surfaces of quasi-spherical shells surrounding large voids, with rich clusters occupying the interstitial regions between shells. The CfA and other recent redshift surveys (Haynes and Giovanelli 1986; Da Costa, *et al.* 1988) suggest that shells with radii up to 30 h^{-1} Mpc ($h \equiv H_o/100\text{km s}^{-1}\text{Mpc}^{-1}$) and with a volume filling factor of order unity may be the dominant structures in the Universe.

Although the evidence for the existence of bubbly structure in the redshift surveys is visually compelling, it remains largely qualitative and anecdotal. Nevertheless, we would like to know whether the bubble paradigm of large-scale structure is an accurate representation of the galaxy distribution, quantitatively consistent with the observed clustering properties of galaxies. In particular, can a structure dominated by bubbles reproduce the galaxy correlation functions? In this paper, we address these questions by studying galaxy statistics in a class of simple phenomenological models: *most* galaxies (*shell* galaxies) are distributed randomly on thin spherical shells surrounding voids; in addition, some galaxies are placed in clusters located at the intersections of three shells (*cluster* galaxies), and others are distributed in a random, uniform background (*background* galaxies). We assume the shells themselves are distributed in a random Poisson process, *i.e.*, they are uncorrelated. We present results for an arbitrary distribution of shell sizes and apply them specifically to the case of a power law distribution of shell radii, $n_{sh}(R) \propto R^{-\alpha}$, truncated at small ($R_{min}$) and large ($R_{max}$) radii.

Observationally, the galaxy two-point correlation function $\xi_{gg}(r)$ is well established and fitted by the power law

$$\xi_{gg}(r) = (r/r_o)^{-\gamma_o}. \tag{1.1}$$

From angular correlation studies of the Lick catalog and other samples (Groth and Peebles 1977), the slope was found to be $\gamma_o = 1.77 \pm 0.04$ and the correlation length $r_o \simeq 4.7h^{-1}$ Mpc, in the range 0.05 h^{-1} Mpc$\lesssim r \lesssim$9 h^{-1} Mpc. These values are consistent with those obtained from the early CfA1 redshift survey data (Davis and Peebles 1983) and from the Southern Sky and IRAS catalogs (Davis, *et al.* 1988). On the other hand, from the first two slices of the CfA redshift survey extension, de Lapparent, Geller, and Huchra (1988) found $\gamma_o = 1.6 \pm 0.3$ and $r_o = 7.5^{+4.5}_{-2.5}$ h^{-1} Mpc in the range of separation $\sim 3 - 14$ h^{-1} Mpc, and noted the large uncertainties. At separations larger than about 10 h^{-1} Mpc, $\xi_{gg}(r)$ appears to steepen and generally becomes lost in the noise at $r \sim 20$ h^{-1} Mpc.

Recent angular correlation studies with larger samples (Collins, Heydon-Dumbleton, and MacGillivray 1989; Maddox *et al.* 1990; Picard 1991) have found a power-law behavior of $w(\theta)$ on small separations ($\theta \lesssim$2deg) with an amplitude agreeing with each other. However, on larger separations, the observed $w(\theta)$'s do not agree with each other. In particular, from the Edinburgh-Durham survey, Collins, Heydon-Dumbleton and MacGillivray (1989) have found a break on an angular scale corresponding to a physical scale $\sim 7h^{-1}$Mpc, which agrees with the break observed by Groth and Peebles (1977) from the Lick catalog. On the other hand, from the APM survey, Maddox *et al.* (1990) have found a more gentle break at $\sim 10h^{-1}$Mpc and reported substantially more power on larger separations than the Lick catalog.

II. SPATIAL TWO-POINT CORRELATION FUNCTION

The spatial two-point correlation function of galaxies $\xi_{gg}(r)$ is defined by

$$\delta P = n_g \delta V[1 + \xi_{gg}(r)]. \tag{2.1}$$

Here, δP is the conditional probability that, starting at a given galaxy, another galaxy is found in the volume element δV at separation r; n_g is the number density of galaxies.

The calculation of $\xi_{gg}(r)$ for the shell model described in §I is simplified by focusing on a particular class of the model: a power low distribution of shell radii with cutoffs at a maximum and minimum radius. Then, the parameters in the model are following: the differential shell number density

$$n_{sh}(R) = \begin{cases} n_{sh,o}(R/R_{max})^{-\alpha} & \text{if } R_{min} \le R \le R_{max} \\ 0 & \text{otherwise} \end{cases}, \tag{2.4}$$

the galaxy surface number density

$$\mathcal{N}_{sh}(R) = \mathcal{N}_{sh,o}(R/R_{max})^{\beta}, \tag{2.5}$$

the shell volume filling factor

$$f = \int_0^\infty \frac{4}{3}\pi R^3 n_{sh}(R) dR, \tag{2.6}$$

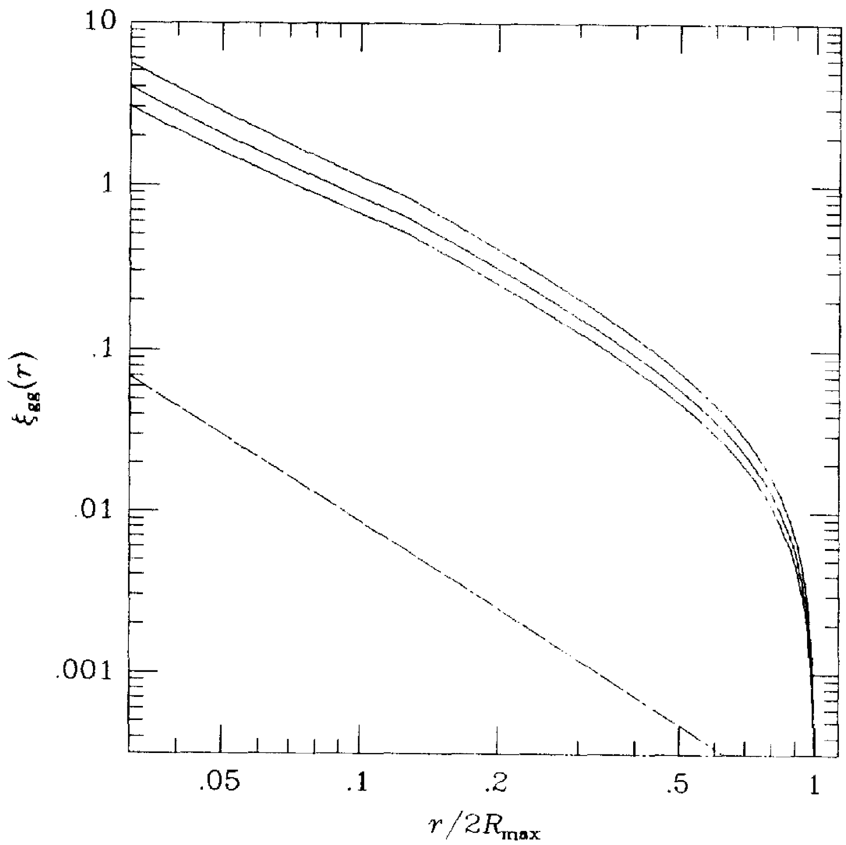

Figure 1. The spatial two-point correlation function of galaxies for the the power law model including cluster and background galaxies. Here, $\alpha = 3.5$, $\beta = 0.0$, $R_{min}/R_{max} = 1/8$, $\delta = 1.0$, $M_c = 0.2$, $M_b = 0.0$ and $f = 0.8$, 1.0, and 1.2. Dashed line corresponding to $r^{-1.8}$ is plotted at lower left for comparison.

and the number of galaxies in clusters formed from three spheres with radii in the intervals R_A, R_B, and R_C,

$$\mathcal{N}_{cl}(R_A, R_B, R_C) = \mathcal{N}_{cl,o}\left(\frac{R_A}{R_{max}}\right)^{\delta}\left(\frac{R_B}{R_{max}}\right)^{\delta}\left(\frac{R_C}{R_{max}}\right)^{\delta}. \tag{2.7}$$

Additional parameters are the fraction of cluster galaxies, M_c, and the fraction of background galaxies, M_b.

Table 1: Model with Cluster and Background Components*

$\alpha = 3.5,\ \beta = 0.0,\ R_{min}/R_{max} = 1/15,\ \delta = 1.0,\ M_s = 0.8,\ M_c = 0.2,\ M_b = 0.0$

f	γ_o	$r_o/2R_{max}$
0.8	1.52	0.087
1.0	1.48	0.071
1.2	1.46	0.060

*Data between $1/20 \leq r/2R_{max} \leq 1/5$ are used to fit the power law form of the two-point correlation function.

The derivation of $\xi_{gg}(r)$ and the resulting $\xi_{gg}(r)$ are quite complicated. Here, we briefly describe the results. The full description for the derivation of $\xi_{gg}(r)$ and the discussion of the results can be found in Ryu, Frieman and Olinto (1991). In Figure 1, $\xi_{gg}(r)$ for $\alpha = 3.5$, $\beta = 0.0$, $R_{min}/R_{max} = 1/8$, $\delta = 1.0$, $M_c = 0.2$, $M_b = 0.0$ and $f = 0.8$, 1.0, and 1.2 is plotted. These values of the parameters, which have shown to reproduce successfully the two-point correlation function of clusters $\xi_{cc}(r)$ (Weinberg, Ostriker, and Dekel 1989), are motivated by the observations and the physics assumed in the model. In Table 1, the slope γ_o and correlation length r_o of $\xi_{gg}(r)$ for the same values of parameters except $R_{min}/R_{max} = 1/15$, are listed. These values were determined by fitting the data between $1/20 \leq r/2R_{max} \leq 1/5$ to the power law form. By considering the simplicity and idealization of the shell mode, we find that the model $\xi_{gg}(r)$ fits the observed $\xi_{gg}(r)$ rather well for the same choice of model parameters which best reproduce $\xi_{cc}(r)$.

III. ANGULAR TWO-POINT CORRELATION FUNCTION

The angular two-point correlation function $w(\theta)$ of galaxies has been calculated from $\xi_{gg}(r)$ using the relativistic version of Limber's equation (Phillipps *et al.* 1978) with $q_0 = 0.5$. For the selection function, we have used the modified Schecter luminosity function (Maddox *et al.* 1990) and a step observer function

$$\mathcal{O}(m) = \begin{cases} 1 & \text{if } m_1 \leq m \leq m_2 \\ 0 & \text{if otherwise.} \end{cases} \tag{3.1}$$

We have chosen $m_1 = 17$ and $m_2 = 20$ to scale $w(\theta)$ to the depth of the APM survey.

Figure 2 shows the resulting $w(\theta)$ converted from $\xi_{gg}(r)$ in Figure 1. For the comparison, the observed $w(\theta)$ by Maddox *et al.* (1990) from the APM survey and by Picard (1991) from the Palomar Observatory Sky Survey are also plotted. On small separations ($\theta \lesssim 2$deg), the calculated $w(\theta)$ agrees with the observed one quite well. The agreement between the calculated $w(\theta)$ and the observed $w(\theta)$ becomes worse at larger separations, ($\theta \gtrsim 3$deg), where the observations also become uncertain. In all the cases we have considered, $w(\theta)$ has more power on large separations ($\theta \gtrsim 4$ deg) than that derived from the APM survey by Maddox *et al.* (1990).

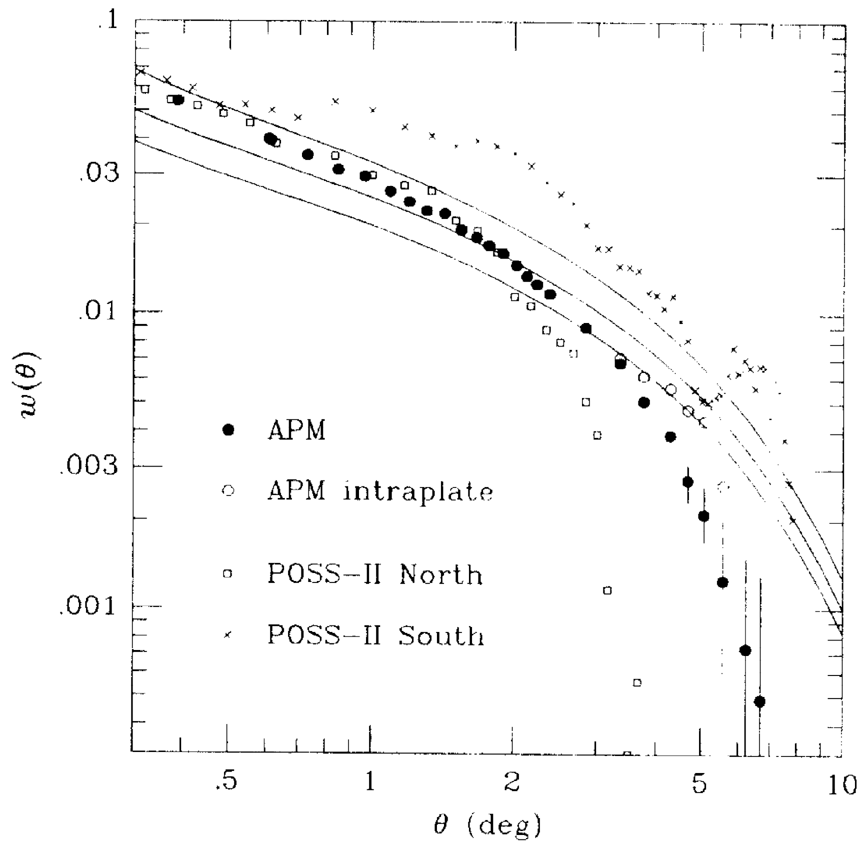

Figure 2. The angular two-point correlation function of galaxies for the the power law model including cluster and background galaxies. Here, $\alpha = 3.5$, $\beta = 0.0$, $R_{min}/R_{max} = 1/8$, $\delta = 1.0$, $M_c = 0.2$, $M_b = 0.0$, $f = 0.8$, 1.0, and 1.2, and $17 \leq m \leq 20$. The observed angular two-point correlation functions by Maddox *et al.* (1990) from the APM survey and by Picard (1991) from the Palomar Observatory Sky Survey are also plotted for comparison.

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