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Are Galaxies More Strongly Correlated than Clusters?

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Abstract:

If the amplitude of the cluster-cluster correlation function is made dimensionless, then systematic changes with cluster richness vanish, implying scale invariance in the clustering process. The dimensionless galaxy-galaxy correlation appears stronger, implying gravitational enhancement on smaller scales.

One of the most powerful tools used to understand the structure of the universe is the correlation function, $\xi_{gg}(r)$, the excess probability over random that there are two objects separated by a distance r. It has been established[1] that for distances out to 10 Mpc, the galaxy distribution has a power-law correlation of the form

$$\xi_{gg}(r) = \alpha_{gg}(hr)^{-1.8}$$

where h is the Hubble constant in units of 100 km/s Mpc.

Recently the spatial correlation function of Abell clusters has been determined directly[2,3], following earlier work on the angular correlations[4]. It was noted, that rich ($R \geq 1$) clusters of galaxies correlate with the same power law as galaxies do, but with a significantly greater amplitude, $\alpha_{cc} = 18\alpha_{gg}$. This amplitude is even higher for richer ($R \geq 2$) clusters. Clusters poorer than most Abell clusters were identified in the Lick catalog by a numerical algorithm[5]. The correlations had the same slope again and the amplitude was between that of galaxies and that of the Abell clusters, in agreement with the trend of richness (see Table 1. for the details of the data).

One of the attempts to explain the behavior of α_{cc} has been made by Kaiser[6] applying the statistics of rare events. If the density perturbations are described by a random Gaussian field, and the regions where clusters form correspond to densities higher than a certain threshold, the correlation function of the points above the 'clipping level' is a constant factor times the correlation function of all the points. By filtering out the scales smaller than clusters from the initial power spectrum and choosing the appropriate threshold, it was possible to match both the number density and enhanced correlations of the Abell clusters. In order to explain the factor of 20 in α_{cc} the clusters have to be $\geq 3\sigma$ points. In this picture $\xi_{cc}(r)$, will have the same functional form as the galaxy autocorrelations. The model may have some difficulties here, since ξ_{gg} appears to be negative at 20 Mpc radii, but ξ_{cc} is positive out to at least 100 Mpc.

The rms peculiar velocities and the correlation amplitude of the mass are related: both originate from the power spectrum of perturbations. The clusters cannot represent the true mass autocorrelations in the universe, since then we would expect to see enormous ($\sim$ few 1000 kms^{-1}) peculiar velocities for the clusters, which does not seem to be the case.

Whenever similar systems of different scales are compared, it is preferential to use dimensionless quantities. The correlation amplitude α_{cc} is dimensional, it is $\xi_{cc}(r)$ at a distance hr = 1 Mpc. It can be made dimensionless by using an intrinsic unit of length for each sample of different richness. The natural length that appears in these point catalogues is the mean separation L, determined by the density $n = L^{-3}$. This mean separation is indeed intrinsic, since there is a unique one-to-one correspondence between richness and the value of L. This is due to the fact, that the richer samples are always subsets of the poorer catalog. Therefore we will label the different richness selections by the value of L. Using this unit, the density of each sample is 1, and the value of the correlation function at L (expressing distance in units of L) is also dimensionless:

$$\beta(L) = \xi(L) = \alpha(L)L^{-1.8}$$

The constant slope in the power law behaviour of $\xi(r)$ indicates scale invariance of the process responsible for galaxy formation. In the case of galaxies the typical distances are a few Mpc, while for clusters the same law holds to distances of more than 50 Mpc. If galaxy formation occurred in a fully scale invariant way, one would expect that all dimensionless correlation amplitudes are equal.

Fig. 1. is a plot of the dimensionless amplitude $\beta(L)$ for all the samples, including the different richness classes of Bahcall and Soneira[2]. Note, that $\beta(L)$ for galaxies is 1.1, a factor of 3 higher than for the cluster samples, which are all consistent with 0.35. As far as clusters are concerned, the scale invariance seems to hold. The correlation amplitudes of the cluster catalogs are fairly well known, the densities are more uncertain. Since L thus $\beta(L)$ depends on the density, we plotted errors on Fig. 1. corresponding to densities 1.5 times above and below the quoted value, representing a conservative error. Compared in this way galaxies are more strongly correlated than clusters are, quite the opposite conclusion to that obtained by comparing $\alpha(L)$.

The relative constancy of $\beta(L)$ can be understood in general terms as a signature of scale invariance. If there is a nonlinear process (besides gravity) modulating galaxy formation, and this process is scale invariant, the created pattern will have a single power law correlation function, the slope of which would be related to the geometry of the pattern, namely to its fractional (or 'fractal') dimension D in the following way[7] :

$$\xi(r)=\beta \ (r/L)^{D-3}$$

This $\xi(r)$ will have the correct scaling property. Thus, in order to explain the observed slope, a fractal dimension of D = 1.2 is required. We do not know yet, what physical process can create the correct D. We discuss several of the possibilities later.

Small scale gravitational clustering may break the scale invariance and increase the dimensionless correlation amplitude for galaxies. In one extreme case we can approximate this process by assuming that the pattern imposed upon the galaxy distribution is uncorrelated with the gravitational motion. Then the observed correlations are a superposition of the gravitational and fractal correlations, with

$$\xi_{frac}(r)=0.35(r/L)^{-1.8},$$

scale invariant, and $\xi_{grav}(r)$ a flat function of r out to about 10 Mpc, independent of L. ξ_{grav} is the Fourier transform of the power spectrum.

$$1+\xi_{obs}(r) = [1+\xi_{grav}(r)][1+\xi_{frac}(r)]$$

If $\xi_{rel}(0)$ is about 3, then we approximately reproduce the observed factor of 3 in $A(L)$.

In the other extreme the process is the nonlinear 'clipping' of the gravitationally induced overdensities [8]. In this case the 'fractal' and the gravitational perturbations are fully correlated. Kaiser has also found a limited scale invariance for that particular model. If the selection is simply due to a threshold in the initial perturbations, which are otherwise scale invariant, the resulting regions, the so called 'excursion sets' will have a scale invariant geometry, they will be fractals[8]. If the universe is dominated by 'cold' dark matter, the fluctuation spectrum has an asymptotic form of k^{-3} where k is the wave number. The larger galaxy correlations in this case can be due to effects of nonlinear gravitational clustering on small scales. From comparisons of the low rms galaxy velocities and the high correlation function of galaxies the necessity for such a 'bias' was suggested recently[9]. All these mechanisms have the advantage of increasing the galaxy correlations while leaving the velocities intact.

Schulman and Seiden[10] have already suggested similarities between condensed matter physics and galaxy formation. Their conclusion, from simple analogies with short range interaction spin systems, was that only fractals with $D \sim 2$ can be obtained.

Gas dynamical processes are bound to occur at some level during galaxy formation. The formation and explosion of first generation PopIII stars[11,12] could have major consequences on the entire galaxy formation scenario. While the energies available in each explosion are not sufficiently large, percolation may occur, creating random structures of 'infinite' length which can yield the required behavior.

Another option is relativistic strings[13,14] which have attracted much attention recently. If present, they may create patterns with a fractal dimension close to 1.

In summary, we propose that galaxy and cluster correlation functions be compared in dimensionless units. The dynamic range of correlation amplitudes has been reduced from 50 to 3. All cluster correlations are consistent with the same scale invariant amplitude. The fact, that in those units galaxies are more strongly clustered may be due to small scale gravitational clustering, while the slope and the dimensionless amplitude may reflect on a scale invariant process responsible for creating luminous galaxies in certain regions of the universe.

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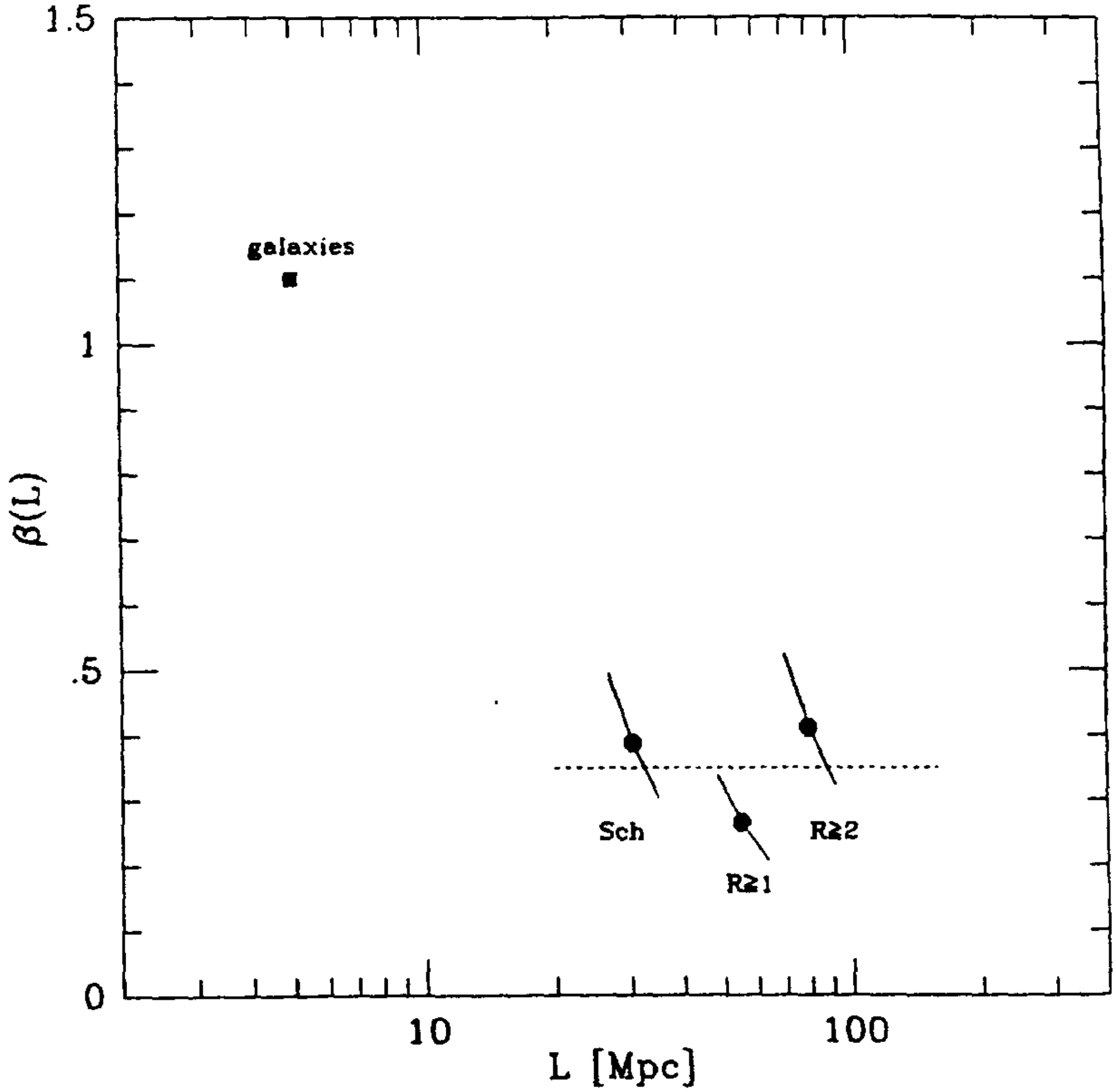

Figure 1. The dimensionless correlation amplitude $\beta(L)$ is shown as a function of the mean separation L. Note, that all three cluster catalogs are consistent with 0.35 (dashed line), while the galaxy amplitude is 1.1. The *error*-bars in the cluster data represent a factor of 1.5 up/down uncertainty in the density.