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Letter to the Editor

Luminous superclusters: remnants from inflation?

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ABSTRACT

Aims. We compile a supercluster sample using the Sloan Digital Sky Survey Data Release 4, and reanalyse supercluster samples found for the 2dF Galaxy Redshift Survey and for simulated galaxies of the Millennium Run.

Methods. We find for all supercluster samples Density Field (DF) clusters, which represent high-density peaks of the class of Abell clusters, and use median luminosities of richness class 1 DF-clusters to calculate relative luminosity functions.

Results. We show that the fraction of very luminous superclusters in real samples is about five times greater than in simulated samples.

Conclusions. Superclusters are generated by large-scale density perturbations that evolve very slowly. The absence of very luminous superclusters in simulations can be explained either by incorrect treatment of large-scale perturbations, or by some yet unknown processes in the very early Universe.

Key words. cosmology: large-scale structure of Universe – galaxies: clusters: general

1. Introduction

Superclusters are the largest density enhancements in the Universe of common origin. Superclusters evolve slowly and contain information from the very early Universe. The investigation of large systems of galaxies was pioneered by the study of the *Local Supercluster* by de Vaucouleurs (1953), and by Abell (1958, 1961), who considered them as *"clusters of clusters"*. Until recently, superclusters have been found mostly on the basis of catalogues of rich clusters of galaxies by Abell (1958) and Abell et al. (1989) (Zucca et al. 1993; Einasto et al. 1994, 1997 (hereafter E97), 2001; Kalinkov & Kuneva 1995).

Superclusters consist of galaxy systems of different richness: single galaxies, galaxy groups and clusters, aligned to chains (filaments). This was realized by Jõeveer et al. (1978), Gregory & Thompson (1978), Zeldovich et al. (1982), and has been confirmed by recent studies of superclusters using new deep galaxy surveys, such as the Las Campanas Galaxy Redshift Survey, the 2 degree Field Galaxy Redshift Survey (2dFGRS, Colless et al. 2001, 2003) and the Sloan Digital Sky Survey Data Release 4 (SDSS DR4, Adelman-McCarthy et al. 2006). New galaxy redshift surveys are almost complete in a fixed apparent magnitude interval. This allows one to estimate total luminosities of superclusters using weights, inversely proportional to the number of galaxies in the observational window of apparent magnitudes. This possibility has been used in supercluster studies by Basilakos (2003), Basilakos et al. (2001), Erdogdu et al. (2004), Porter & Raychaudhury (2005), and Einasto et al. (2003a,b, 2005, 2006a, hereafter Paper I).

Einasto et al. (2006b, Paper II) analysed properties of 2dFGRS superclusters and compared them with properties of model superclusters of the Millennium Run mock galaxy catalogue by Croton et al. (2006), based on the Millennium Simulation of the evolution of the Universe by Springel et al. (2005). This comparison of real superclusters with simulated ones shows that geometric properties of simulated superclusters agree very well with similar properties of real superclusters. However, one property of model superclusters is in conflict with observations: real samples have many more very luminous superclusters than model samples. The presence of very massive superclusters in our neighborhood is well known, examples are the Shapley and Horologium-Reticulum Superclusters (see Fleenor et al. 2005; Proust et al. 2006; Nichol et al. 2006; Ragone et al. 2006 and references therein). However, until recently the number of such extremely massive superclusters was too small to make definite conclusions on the phenomenon.

The goal of this Letter is to compile a new catalogue of superclusters on the basis of the SDSS DR4, to determine the luminosity and multiplicity functions of SDSS DR4 and 2dFGRS superclusters, and to compare these functions with similar functions of simulated superclusters. This is presently the largest collection of real and model superclusters, and allows us to make definite conclusions on the statistics of luminous superclusters. Our supercluster catalogues, as well as fits files of luminosity density fields are available electronically at `http://www.aai.ee/~maret/DR4scl.html`, 2dFGRS and SDSS supercluster catalogues are also available at the CDS via `anonymous ftp to cdsarc.u-strasbg.fr` or via `http://cdsweb.u-strasbg.fr`.

Table 1. Data on supercluster samples.

Sample	$N_{\rm gal}$	V	$N_{\rm cl}$	$N_{\rm scl}$	N_1	L_1
SDSS	197 481	43.9	2709	911	471	7.86e+11
2dFc	184 395	30.3	1907	544	271	7.66e+11
Obs	381 876	74.2	4616	1455	742	7.79e+11
Mill.A8	8 964 936	125	2878	1733	1025	2.10e+12
Mill.F8	2 094 187	125	1687	1068	752	3.03e+12
Mill.F8c	2 094 187	125	3161	1430	848	2.91e+12

Notes: in the sample 2dFc we used of corrected density field of 2dFGRS as described above, Obs is the combined observational sample, Mill.F8c is a test sample derived with a threshold density 5.0, $N_{\rm gal}$ is the number of galaxies used in the determination of the density field and the luminosity of superclusters; V is the volume (in million cubic h^{-1} Mpc); $N_{\rm cl}$ is the number of DF-clusters in the sample; $N_{\rm scl}$ and N_1 are the total number of superclusters, and the number of superclusters of multiplicity 1, respectively. L_1 is the mean luminosity of superclusters of multiplicity 1, expressed in Solar units, $L_\odot/h^2$.

2. Data

To compile a new supercluster catalogue we used Data Release 4 of the SDSS by Adelman-McCarthy et al. (2006). In the present analysis we used only the contiguous high-declination zone of DR4. The supercluster catalogue was found in two stages. First we found a group catalogue of DR4 galaxies using a method similar to the method applied in the compilation of the 2dFGRS group catalogue of Tago et al. (2006). We also estimated expected total luminosities of groups using weights of galaxies which take into account galaxies and galaxy groups too faint to fall into the observational window of absolute magnitudes at the distance of the galaxy. This is the conventional approach for obtaining the luminosity density field (Basilakos et al. 2001, Paper I). In the second stage we calculated the luminosity density field smoothed with an Epanechnikov kernel of radius 8 h^{-1} Mpc. Superclusters were defined as connected non-percolating systems with densities above a certain threshold density. The density field was found for a cell size of 1 h^{-1} Mpc, which allows us to investigate in detail the internal structure of superclusters (see Paper II).

To obtain comparable results for the luminosity and multiplicity functions of different samples all data and data reduction procedures must be as similar as possible. The comparison of density fields of SDSS DR4 and 2dFGRS showed the presence of differences in threshold bias levels. In our analysis we use relative densities expressed in units of the mean density of the particular galaxy sample. If in galaxy samples the fraction of faint galaxies is different, this leads to different mean densities (for a detailed discussion of this effect see Einasto et al. 1999). We take the density field of the SDSS DR4 sample as the basic one (it forms a contiguous area on the sky and contains more galaxies than the Northern and Southern regions of 2dFGRS taken together, see Table 1). To bring the density field of the 2dFGRS to the same level as the SDSS field, we divided the 2dFGRS field by 0.739 (this factor was found from the comparison of peak densities of both fields).

For comparison to the observational data sets we used the mock galaxy catalogues based upon the Millennium Simulation by Croton et al. (2006). We used two versions of the simulation, with all simulated galaxies included, Mill.A8, and a version using similar selection criteria as in the 2dFGRS sample, Mill.F8. Density fields of the SDSS DR4 and Millennium Run galaxies have approximately equal threshold bias levels, thus no correction of the density field was needed.

To characterise the richness of superclusters we use density field (DF) clusters, defined as high-density peaks of the density field, smoothed on a scale of 8 h^{-1} Mpc. We define the multiplicity of a supercluster by the number of DF-clusters in it. We analysed properties of supercluster and DF-cluster samples derived for a series of threshold densities. This analysis shows that the optimal threshold density to define superclusters is 6.0 in units of the mean density, and 6.5 to find DF-clusters. With these threshold densities we selected SDSS superclusters and DF-clusters, and reselected 2dFGRS and Millennium superclusters and DF-clusters. The main characteristics of all supercluster catalogues are summarized in Table 1. The threshold density 6.0 for the corrected density field of the 2dFGRS sample corresponds to a threshold density of 4.4 in the uncorrected density field, very close to the value 4.6 used in Paper I to find 2dFGRS superclusters. Thus the number of superclusters and their parameters is very close to the respective data used in Paper I.

3. The luminosity and multiplicity functions of superclusters

We use two independent parameters to quantitatively characterise the richness of a superclusters: the multiplicity and the total luminosity. The spatial density of DF-clusters in our observational samples is 62 per million cubic h^{-1} Mpc, about twice the spatial density of Abell clusters, 25 per million cubic h^{-1} Mpc (E97). Thus the expected multiplicity of superclusters is about two times higher than the multiplicity of Abell superclusters of Einasto et al. (2001).

The other integral parameter of a supercluster is its total luminosity, determined by summing luminosities of all galaxies and groups of galaxies inside the threshold iso-density contour which was used in the definition of superclusters. The colour systems of our samples are different: `r` in SDSS and Mill.A8, `bj` in 2dFGRS and `g` in Mill.F8. The other difference is between observational and model data in general: mean luminosities of main galaxies and superclusters of the mock catalogue are higher than in real samples by a factor of 2–4. The reason for this difference is not clear. We are interested in the relative fraction of rich and very rich superclusters relative to the number of poor superclusters. To avoid complications due to the use of different color systems and mean luminosities, we define *relative* luminosities as the luminosity in terms of the mean luminosity of poor superclusters, i.e. superclusters that only contain one DF-cluster and hence are classified as richness class 1. The distribution of luminosities is approximately symmetrical on a logarithmic scale. We therefore used the logarithm of the luminosity to derive the mean value. This value, L_1, is also listed for all samples in Table 1, in units of the Solar luminosity.

In Fig. 1 we show the relative luminosity functions (left panel) alongside the multiplicity functions (right panel) for the observational and model samples. The most striking feature of the Figure is the demonstration of the presence of numerous very luminous superclusters in observational samples, and the absence of such systems in simulated samples. This difference between real and simulated supercluster richness is well seen using both richness criteria, the multiplicity and luminosity functions. When comparing models with observations we have to use the sample Mill.F8, which is formed using similar selection criteria as observational samples. Most luminous simulated superclusters of the Mill.F8 sample have a relative luminosity of about 15 in terms of the mean luminosity of richness class 1 superclusters, most luminous superclusters of real samples have a relative

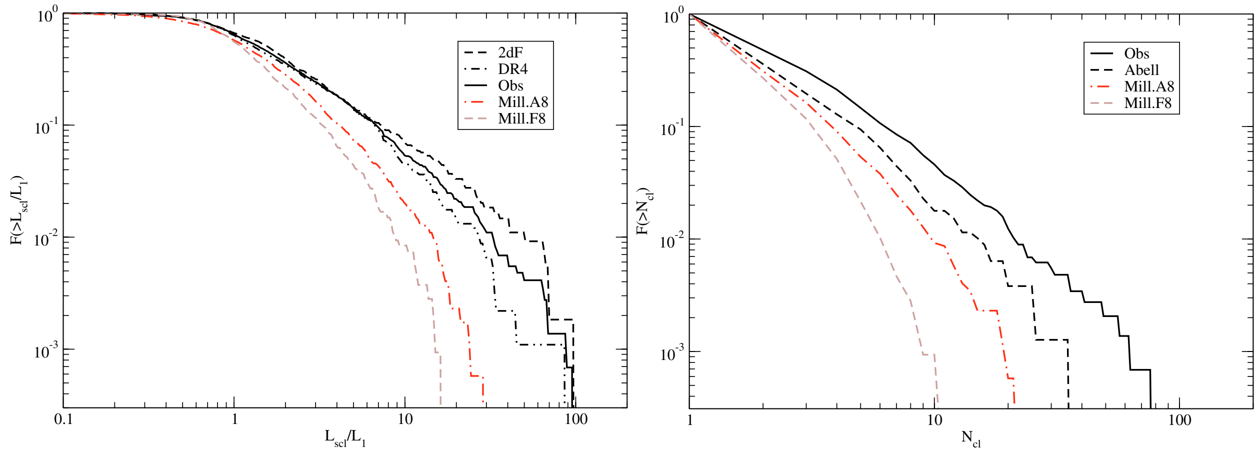

Fig. 1. The comparison of relative luminosity functions and multiplicity functions of observational and model supercluster samples. The spatial density of superclusters is expressed in terms of the total number of superclusters in the respective sample to avoid small differences due to the mean number density of superclusters in different samples. In the left panel we show relative luminosity functions separately for observational samples SDSS DR4, 2dF and the combined sample Obs, in the right panel we plot the multiplicity function of the combined observational sample Obs, and the Abell supercluster sample (here multiplicity is defined by the number of Abell clusters, isolated Abell clusters are considered as richness class 1 superclusters).

luminosity of about 100, i.e. they are about 6 times more luminous. The richest model superclusters of the sample Mill.F8 have a multiplicity of 10, whereas real superclusters have over 70. The number of Abell clusters in the richest Abell supercluster is 34 (Einasto et al. 2001). The differences between real and simulated samples are observed not only in the region of most luminous superclusters: over the whole richness scale the number of DF-clusters in simulated samples is smaller than in real superclusters, and the relative luminosity function lies lower.

We note that very luminous superclusters are located in *all subsamples* (Northern and Southern regions of 2dFGRS, and in subregions of the SDSS DR4 sample, if divided into 3 wedges of equal width). These subsamples have characteristic volumes of about 10 million cubic h^{-1} Mpc, whereas model samples of 10 times larger volume have no extremely rich superclusters.

The mean and peak luminosity densities of rich superclusters are much higher than the respective densities of poor superclusters, which demonstrates that rich superclusters are not due to a percolation of several poorer superclusters. Several very rich superclusters of the 2dFGRS samples are known from earlier studies. One of the richest superclusters of the Northern sample is SCL126 of the catalogue by E97, also known as the Sloan Great Wall (Vogeley et al. 2004). It contains 7 Abell clusters, 5 of them X-ray clusters, and 18 DF-clusters. DF-clusters form in this supercluster two very dense concentrations joined by a bridge of luminous groups of galaxies. The richest supercluster in the Southern sample is SCL9 by E97, or the Sculptor Supercluster, containing 24 Abell clusters (6 of them are X-ray clusters), and 30 DF-clusters. For comparison we note that the Shapley and Horologium-Reticulum Superclusters contain 34 and 26 Abell clusters, respectively; about one third of them are X-ray clusters. The number of X-ray clusters in poor superclusters is very small (see Einasto et al. 2001).

Mean luminosities of galaxies and DF-clusters in superclusters of different richness are similar. Both real and simulated superclusters of richness class 1 have a large spread of volumes and luminosities, i.e. they contain one DF-cluster surrounded by filaments of galaxies and groups of galaxies of various length and number. But there exist important differences. In mock samples the bridges between DF-clusters are weak in most superclusters, and density knots in filaments do not exceed the threshold needed to form a DF-cluster. For this reason the spatial density of DF-clusters and superclusters is lower in the mock sample. Mill.F8 superclusters fill only 0.7% of the total space, and the fraction of galaxies in superclusters is 9.2%. In contrast, SDSS superclusters occupy 3.4% of the space and contain 26.7% of all galaxies. Because galaxy filaments (and galaxy groups within filaments) of the mock samples are weaker, especially in the sample Mill.F8, most mock superclusters contain only one DF-cluster, also in cases when the DF-cluster is very bright. This explains the high mean luminosity of richness class 1 superclusters, and the absence of very rich superclusters. The smoothness of the luminosity density field of the Millennium Run is seen also in the movie which accompanies the paper by Springel et al. (2005).

To show the sensitivity of results on selection parameters we used model Mill.F8c, applying threshold density 5.0 instead of 6.0 in selecting superclusters, see Table 1. The relative luminosity function of this sample is close to the respective function for Mill.A8, i.e. it is not very sensitive to the threshold level. However, the use of a lower threshold violates the rule that we have to use identical selection parameters for real and model data.

4. Luminous superclusters and inflation

Superclusters of galaxies are formed by density perturbations on large scales. These perturbations evolve very slowly. As shown by Kofman & Shandarin (1988), the present structure on large scales is already built-in in the initial field of linear gravitational potential fluctuations. They are remnants of the very early evolution and stem from the inflationary stage of the Universe (see Kofman et al. 1987). The distribution of luminosities of superclusters allows us to probe processes acting at these very early phases of the evolution of the Universe.

There are two possible explanations for the large difference between the distribution of luminosities of real and simulated samples. One possibility is that in present simulations the role of very large density perturbations, responsible for the formation of these very luminous superclusters, is underestimated. If this is the case then this means that our simulations have not yet reached a volume that can be treated as a fair sample of the

Universe. In other words, a fair sample of the Universe has linear dimensions far in excess of 500 h^{-1} Mpc, used in simulations investigated in this Letter. A study of the effects of large-scale perturbations on the properties of dark matter haloes by Power & Knebe (2006) indicates that a suppression of long wavelength perturbations will lead to a depletion of high mass haloes.

The other feasible explanation of the differences between models and reality may be the presence of some unknown processes in the very early Universe which give rise to the formation of extremely luminous and massive superclusters.

It is too early to draw definite conclusions on the character of processes during inflation which may have caused the formation of very massive superclusters. The explanation of the physical origin of very massive superclusters is a challenge for theory. To obtain a more complete observational picture of the phenomenon, large contiguous deep redshift surveys are needed. Only contiguous surveys allow one to detect very massive superclusters. This is one reason why the continuation of the SDSS survey is so important, until the whole Northern hemisphere is covered by redshift data, as originally planned.

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