Formation of the Supercluster-Void Network

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A review of the study of superclusters based on the 2dFGRS and SDSS is given. Real superclusters are compared with models using simulated galaxies of the Millennium Run. We show that the fraction of very luminous superclusters in real samples is about five times larger than in simulated samples. Superclusters are generated by large-scale density perturbations which evolve very slowly. The absence of very luminous superclusters in simulations can be explained either by non-proper treatment of large-scale perturbations, or by some yet unknown processes in the very early Universe.

Introduction

Superclusters are the most extensive density enhancements in the Universe of common origin. Investigation of large systems of galaxies was pioneered by the study of the *Local Supercluster* by de Vaucouleurs (1953) and by Abell (1961) and using rich clusters of galaxies by Abell (1958) and Abell et al. (1989). Superclusters consist of galaxy systems of different richness: single galaxies, galaxy groups and clusters, aligned in chains (Jõeveer, Einasto, & Tago, 1978; Gregory & Thompson, 1978; Zeldovich, Einasto, & Shandarin 1982).

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 (SDSS, Adelman-McCarthy et al. 2006) cover large areas in the sky and are almost complete up to fairly faint apparent magnitudes. Thus these surveys are convenient to detect superclusters using both galaxy and cluster data. This possibility has been used by Basilakos (2003), Basilakos et al. (2001), Erdogdu et al. (2004), Porter & Raychaudhury (2005), and Einasto et al. (2003a, 2003b, 2005, 2006a).

The goal of the present review is to analyse properties of superclusters based on the 2dF Galaxy Redshift Survey and the Sloan Digital Sky Survey Data Release 4 by Einasto et al. (2006a, 2006b, 2006c), and to compare properties of real superclusters with theoretical models. 2dFGRS and SDSS supercluster catalogues have been compiled using group catalogues of 2dFGRS and SDSS DR4 surveys, found by Tago et al. (2006a, 2006b). For comparison we use the superclusters found for the Millennium Run mock galaxy catalogue by Croton et al. (2006), that itself is based on the Millennium Simulation of the evolution of the Universe by Springel et al. (2005).

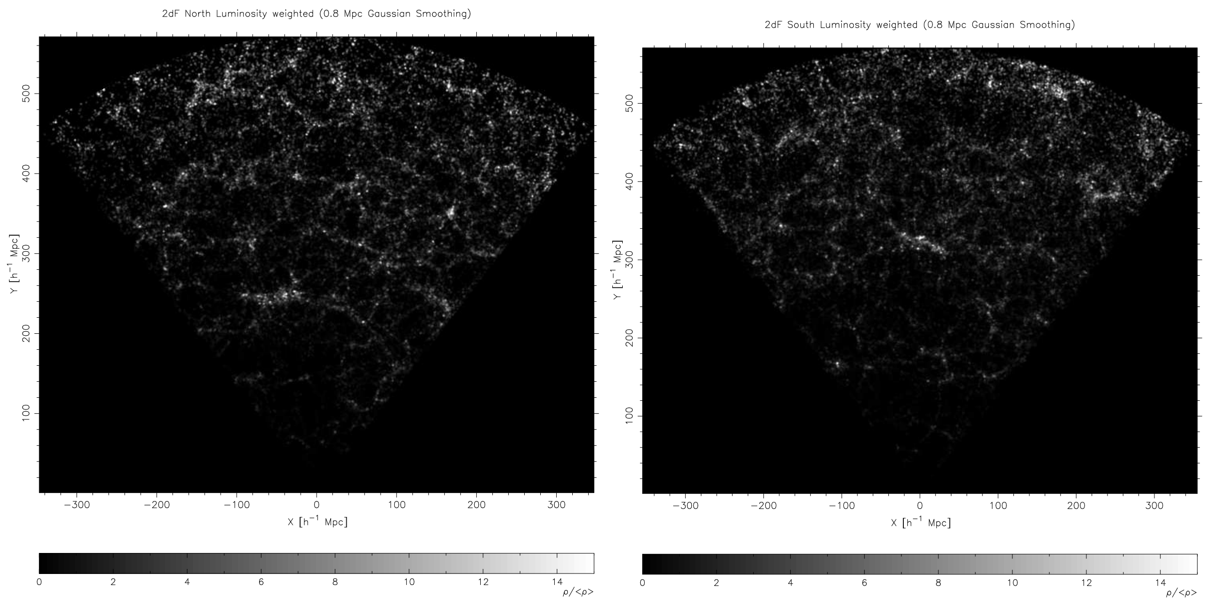

Figure 1: The high-resolution 2-dimensional density fields of the Northern and Southern parts of the 2dF redshift survey are shown in the left and right panels, respectively. The samples are conical, i.e. their thickness increases with distance, thus at large distances from the observer we see many more systems of galaxies. The richest supercluster in the Northern region is SCL126 in the list by Einasto et al. (1997), also called the Sloan Great Wall by Vogeley et al. (2004); the richest Southern supercluster is SCL9 by Einasto et al. (1997), or the Sculptor Supercluster.

Superclusters in the 2dF and Sloan surveys and in the Millennium simulation

Both real and model superclusters were found using the luminosity density fields calculated using Epanechnikov smoothing with a radius of 8 h^{-1} Mpc. Superclusters were defined as connected non-percolating systems with densities above a certain threshold density. These density fields were normalized to identical mean levels, and all regions above a threshold density 6 (in units of the mean density) were considered as superclusters. The density fields were calculated for a grid step of 1 h^{-1} Mpc, which allows to investigate the detailed spatial structure of superclusters. The 2dFGRS superclusters were found separately for the Northern and Southern regions of the 2dF Survey, and SDSS superclusters – for the high-declination region of the SDSS DR4 Survey in the Northern hemisphere. The 2dF Northern and Southern regions together contain 544 superclusters, the SDSS Northern survey has 911 superclusters. The comparison model samples have 1733 and 1068 superclusters (the full model sample and the simulated 2dF sample, respectively).

In *Figs. 1* and *2* we show high-resolution density fields on the 2dFGRS and SDSS surveys. All wedges are about 10 degrees thick, thus near to the observer they are thin. These figures show the cosmic web – a continuous network of galaxy systems of various

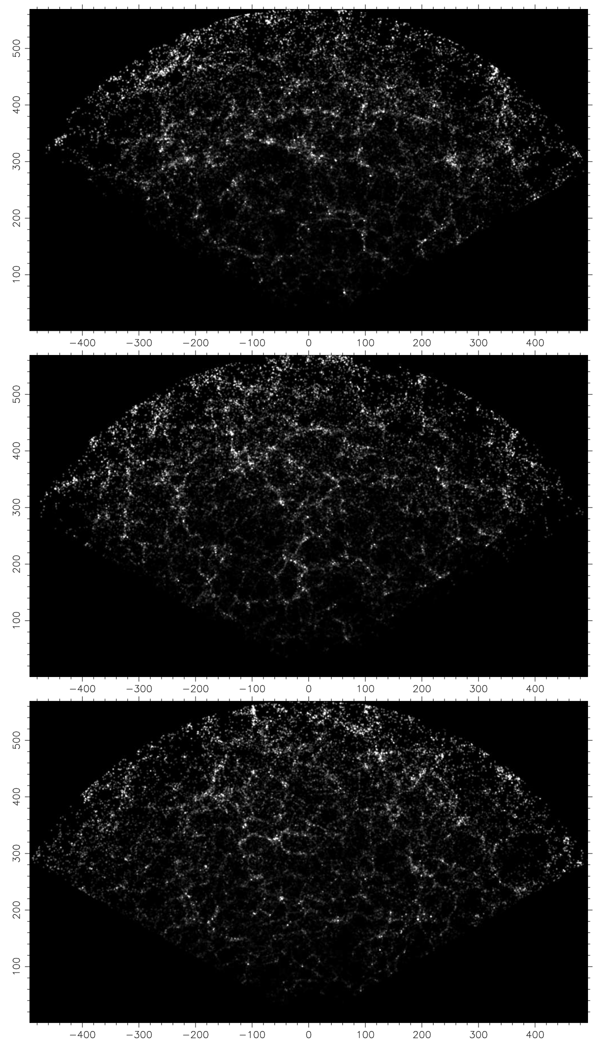

Figure 2: The high-resolution 2-dimensional density field of the SDSS DR4 Northern high-declination region. The wedges are drawn in rectangular coordinates based on the SDSS survey coordinates η and λ, and have a thickness of 9.33 degrees in λ; the panels from bottom to top correspond to increasing λ values. Note the presence of rich superclusters in all wedges.

luminosity densities, and voids between them. All luminous regions seen in these figures are superclusters. We see that they have very different richness, some are very small and resemble the Local Supercluster around the Virgo cluster, some are large and very rich.

For all superclusters their geometric and physical properties were found. Among the geometrical properties are the position (RA, DEC, and distance), the size, and the offset of the geometrical center from the dynamical one, defined as the center of the main (most luminous) cluster. The physical properties are the mean and maximum luminosity densities, the total luminosity and the luminosity of the main cluster and of the main galaxy (the brightest galaxy of the main cluster).

Comparison of properties of model superclusters with properties of real superclusters shows that they are very similar. Superclusters consist of several chains (filaments) of galaxies, groups, and clusters. These chains have various length, thus superclusters are asymmetrical in shape. The degree of asymmetry is higher in rich superclusters. Rich superclusters are also denser and contain luminous knots – high-density nuclei.

Rich superclusters in real data and models

One important property of superclusters is different in real and model samples – the supercluster richness. To characterise the richness we used two independent characteristics: the total luminosity and the number of rich clusters, i.e. the multiplicity.

The multiplicity was derived from the number of high-density knots of the density field. We call these knots DF-clusters. The spatial density of DF-clusters is about twice that of Abell clusters in the same volume, thus the expected number of DF-clusters in superclusters is about twice the number of Abell clusters. Both functions were determined separately for the 2dFGRS and SDSS superclusters, and for the total observational sample.

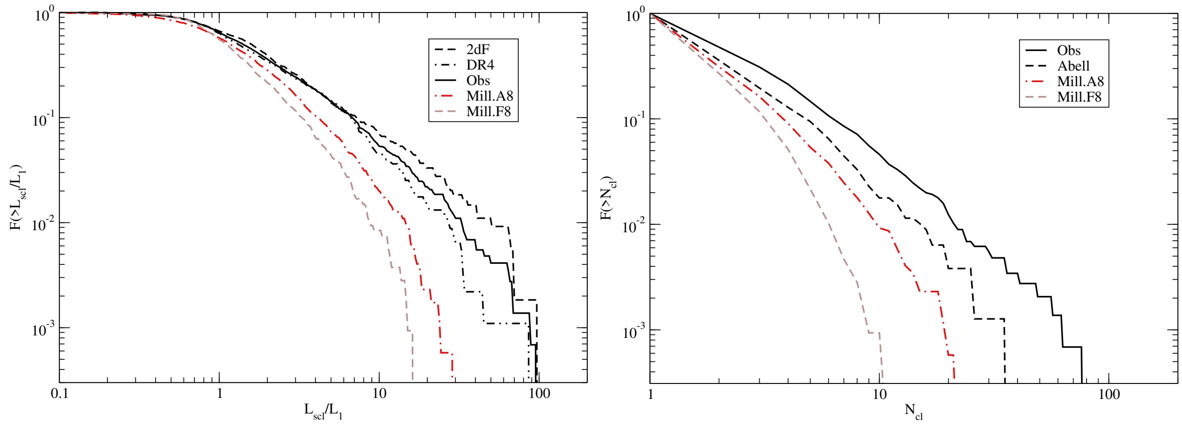

Figure 3: Comparison of relative luminosity functions and multiplicity functions of observational and model supercluster samples (in left and right panels, respectively). The spatial density of superclusters is expressed in terms of the total number of superclusters in a sample to avoid small differences due to different mean supercluster number densities in different samples. In the left panel we show the relative luminosity functions separately for the observational samples SDSS DR4, 2dF, and for the combined sample Obs, in the right panel we use the combined observational sample Obs, and the Abell supercluster sample (here the multiplicity is defined by the number of Abell clusters, and isolated Abell clusters are considered as richness class 1 superclusters). Mill.A8 and Mill.F8 denote the full and simulated 2dF Millennium supercluster samples, respectively.

The total luminosity was calculated by summing the luminosities of galaxies and clusters of galaxies inside the density contour, which defines the boundary of the supercluster. In our case the threshold density was chosen to be 6 (in units of the mean density). In calculating total luminosities we used weights for galaxies which take into account the galaxies outside the observational luminosity window of a survey. To avoid complications due to the use of different color systems and mean luminosities, we used *relative* luminosities, normalized by the mean luminosity of poor superclusters, i.e. the superclusters that contain only one DF-cluster.

For model samples we calculated these functions for two cases. One sample uses all model galaxies and can be considered as the “true” model sample. The second model sample simulates the 2dF sample, where an “observer” was put into one corner of the sample, and only these galaxies were included, which satisfy the same selection criteria as used in the real 2dF sample.

The luminosity and multiplicity functions of real and model samples are compared in *Fig. 3.* We see that both functions show much more rich superclusters for real samples than for model samples. This difference is the major cosmological result of the analysis of our supercluster survey. The presence of very rich superclusters in our vicinity is well known; good examples are the Shapley Supercluster and the Horologium-Reticulum Supercluster (see Fleenor et al., 2005; Proust et al., 2006; Nichol et al., 2006; Ragone et al., 2006, and references therein). But until recently the number of such extremely massive superclusters was too small to make definite conclusions about their abundance.

When comparing models with observations we have to use the simulated 2dF sample, which is formed using the same selection criteria as used for the observational sample. The most luminous simulated superclusters of this sample have a relative luminosity of about 15 in terms of the mean luminosity of richness class 1 superclusters, whereas the most luminous superclusters of real samples have a relative luminosity about 100, i.e. they are about 6 times more luminous. The richest model superclusters have a multiplicity of 10, whereas the multiplicity of the richest real superclusters is over 70. The number of Abell clusters in the richest Abell supercluster is 34 (Einasto et al., 2001).

Figures 1 and *2* show that very luminous superclusters are located in *all subsamples* (the Northern and Southern regions of the 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.

Formation of the supercluster-void network

To check these results we used a number of independent numerical simulations, carried out for simulation boxes of size of 500 h^{-1} Mpc and 768 h^{-1} Mpc, using 512^3 Dark Matter particles. We found DM-halos in simulations, and used them to calculate the smoothed density field as for real and Millennium Simulation. For all simulations we then found simulated superclusters as previously, and found the distribution of dense knots (simulated rich clusters). These calculations confirmed our previous result: the number of dense knots in simulated superclusters is much smaller than in real superclusters.

This striking conflict between model and reality needs explanation. In order to understand the formation of rich superclusters we used wavelet analysis to investigate the role of density waves of different scales. The á trous wavelet technique we used allows to divide the density field into components of various wavelength bands, so that the field is restored by summing all components. The wavelet analysis was carried out both for real and model samples.

Our results show that in all cases superclusters form only in regions where *large density waves combine in similar local phases to generate high density peaks*. Very rich superclusters are objects where density waves of all large scales (up to a wavelength $\sim 250\ h^{-1}$ Mpc) have similar phases. The smaller is the maximum wavelength of such phase synchronization, the lower is the richness of superclusters. Similarly, large voids are caused by large-scale density perturbations of wavelength $\sim 100\ h^{-1}$ Mpc, here large-wavelength modes combine *in similar local phases to generate under-densities*.

Superclusters of galaxies are formed by density perturbations of large scales. These perturbations evolve very slowly. As shown by Kofman & Shandarin (1988), the present structure on large scales is built-in already in the initial field of linear gravitational potential fluctuations. Actually 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. 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.

Conclusions

1. Geometric properties of superclusters are well explained by current models.
2. There are much more very rich superclusters than models predict.
3. Large perturbations evolve very slowly and represent the fluctuation field at the epoch of inflation.
4. The difference between observations and models can be explained in two ways:
   large-scale perturbations are not incorporated in the models, i.e. models need improvement;
   there occurred presently unknown processes during inflation.

The present review is based on talks held in Budapest on April 20, 2006 in Detre Centenary, in Uppsala University on April 27, 2006, and in Aspen Workshop on Cosmic Voids on June 6, 2006. I thank my collaborators Maret Einasto, Enn Saar, Erik Tago, and Volker Müller for permission to use results of our common work in this review. We are pleased to thank the 2dFGRS and SDSS Teams for the publicly available data releases. The present study was supported by Estonian Science Foundation grants No. 4695, 5347, and 6104, and Estonian Ministry for Education and Science support by grant TO 0060058S98. I thank Astrophysikalisches Institut Potsdam (using DFG-grant 436 EST 17/2/05) and Uppsala University for hospitality where part of this study was performed. 2dFGRS supercluster catalogues are available at `http://www.aai.ee/~maret/2dfscl.html`, Sloan DR4 supercluster catalogues at `http://www.aai.ee/~maret/SDSSDR4scl.html`.

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