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ON THE LARGE-SCALE PERIODICITY IN THE SPATIAL DISTRIBUTION OF RICH CLUSTERS OF GALAXIES

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Abstract. In a study of the large voids in the spatial distribution of Abell/ACO clusters of galaxies in the Northern Galactic Hemisphere we have analysed the variations with redshift of the number density of clusters in a large solid angle (galactic latitude $b \geq +30°$) and to a limiting redshift $z \sim 0.2$, as well as the spatial distribution of large voids to $z \leq 0.14$. Two samples of clusters (1) with measured redshifts and (2) with measured or photometrically estimated redshifts have been used. While the first sample shows two maxima in the number density distribution at $z \sim 0.03$ and $z \sim 0.07$–0.08, known from previous studies, the second one shows also a well defined third maximum at $z = 0.12$–0.14 which coincides roughly with the third of the peaks in the number of galaxies towards the North Galactic Pole discovered by Broadhurst et al. (1990). The analysis of the spatial void distribution suggests the presence at $z \sim 0.07$–0.08 of a giant 2-D structure, composed of several known superclusters. We propose an explanation of the third density maximum at $z = 0.12$–0.14 as a combined effect of (1) the systematic overestimate of m_{10} – the magnitude of the tenth brightest cluster member – in Abell's catalogue which has affected our estimated redshifts, and (2) the presence in the redshift range 0.12–0.14 of another giant 2-D structure. The existence of the two large-scale structures is in agreement with a quasi-periodic distribution of the rich clusters of galaxies with a period $\Delta z \sim 0.05$.

1. INTRODUCTION

Using deep pencil-beam redshift surveys of galaxies in direction to the North and South Galactic Poles to $z \lesssim 0.3$ Broadhurst et al. (1990, hereafter BEKS) discovered a surprising regularity in the redshift distribution with most galaxies lying in discrete peaks with roughly equal separation of 128 h^{-1} Mpc (hereafter $H_0 = 100\,h$ km s^{-1} Mpc^{-1}). This unexpected result was later confirmed by the same authors on the basis of new 1-D surveys directed away off the galactic poles (Koo et al. 1993), as well as by other authors who used more or less deep samples of galaxies at different locations on the celestial sphere (Ettori et al. 1997, Vettolani et al. 1997, Drinkwater et al. 2000). Periodicity with a smaller characteristic scale has been also found in the redshift distribution of galaxies in the Hubble Deep Field (Williams et al. 1996) for the redshift range $z = 0.3$–1.1 (Cohen et al. 2000).

Strong evidence for the apparently periodic distribution of galaxies, as well as an explanation of this phenomenon, came from the analysis of wide-angle cluster samples. Bahcall (1991) was the first to show that the observed peaks in the redshift distribution of galaxies originate from the intersections of the narrow-beam surveys with the regions of known extended superclusters. Thus, the regularity in the distribution of galaxies is consistent with a description of the large-scale structure of the Universe as a network of superclusters and large voids with a typical mean separation of $\sim$ 100–150 h^{-1} Mpc. The structural reality of the peaks in BEKS survey has been confirmed also by Tully et al. (1992) and Guzzo et al. (1992) on the basis of deeper samples of rich clusters of galaxies. The former authors show that the periodicity maxima deliniated by BEKS coincide with giant structures composed of rich clusters which span over several hundred h^{-1} Mpc in directions orthogonal to the supergalactic plane (i.e. parallel to the galactic plane). Let us note that similar huge structure (stratum) with dimension $\sim$ 500 h^{-1} Mpc and roughly parallel to the galactic plane has been detected earlier by Kopylov et al. (1988) in the distribution of rich Abell clusters (richness class $R \geq 2$) towards the northern galactic cap at $z = 0.16$–0.18.

As some authors have shown, the existence of regularity in the distribution of galaxies with a characteristic scale $\gtrsim$ 100 h^{-1} Mpc leads to the appearance of a local peak in the power spectrum and to an oscillating correlation function. E.g. Einasto et al. (1997a, 1997b) obtain a power spectrum for the Abell clusters of galaxies with a well defined peak at a wavenumber $k = 0.05\ h\ \ \mathrm{Mpc}^{-1}$, corresponding to a wavelength of 120 h^{-1} Mpc, and an oscillating correlation function with regularly spaced secondary maxima and minima with a period of the oscillations 115 h^{-1} Mpc. This regularity is in contradiction with the standard theory of large-scale structure formation which predicts random distribution of the galaxies and clusters of galaxies on large scales. The origin of a large-scale periodicity can be explained by barionic acoustic oscillations during the early stages of the evolution of the Universe. However, as Eisenstein et al. (1998) have shown such an explanation requires too large baryon fraction in disagreement with the big bang nucleosynthesis constraints. To overcome the difficulties encountered in the frames of the standard structure formation scenario Kirilova & Chizhov (2000) propose a completely different mechanism of non-gravitational origin producing baryon density perturbations during the inflationary stage of the Universe which evolve into baryonic shells devided by vast underdence regions.

Up to now several of the nearest peaks in BEKS redshift distribution have been identified with large structures (superclusters, walls). As shown by Bahcall (1991) the first two northern and the first two southern peaks coincide with known superclusters from the catalogue of Bahcall & Soneira (1984, hereafter BS). The first northern peak ($z \sim 0.02$) is due to the Coma and Hercules superclusters (BS10, BS15) which form an extended flat structure in the distribution of galaxies, called "the Great Wall" (Geller & Huchra 1989). The second northern peak ($z \sim 0.08$) corresponds to the Corona Borealis supercluster (BS12). The first southern peak ($z \sim 0.02$) originates from the Perseus-Pisces supercluster (BS19), and the second southern peak ($z \sim 0.06$) is due to several superclusters (BS1–3, BS20). Tully et al. (1992) and Guzzo et al. (1992) have identified the third southern maximum at $z \sim 0.11$ with the Sculptor supercluster (Seitter et al. 1989).

In this paper we present some new evidence for the structural reality of the second and third northern peaks in the redshift distribution observed by BEKS. We show on the basis of the analysis of deeper and more complete samples of rich clusters of galaxies that these peaks indicate the existense of huge 2-D structures composed of rich clusters extending roughly parallel to the galactic plane and separated by large voids. This result is consistent with the existence of a large-scale regularity in the spatial distribution of clusters of galaxies.

2. THE CLUSTER SAMPLES

We use two samples of rich clusters (richness class $R \geq 1$) from the catalogues of Abell (Abell 1958) and ACO (Abell, Corwin & Olowin 1989; hereafter ACO). The samples are limited in the Northern Galactic Hemisphere. The redshift data for the clusters have been compiled from four sources (Lebedev & Lebedeva 1996; NASA/IPAC Extragalactic Database; Slinglend et al. 1998; Andernach & Tago 1998). Details on the compilation of the redshift data and the preparation of the cluster samples are given in Stavrev (2000).

The first sample (sample AR/L) contains only clusters with spectroscopically measured redshifts. The number of objects in this sample for a limiting redshift $z \leq 0.2$ and a limiting galactic latitude $b \geq +30°$ is 486.

In order to increase the completeness of the first sample at larger distances we form a second sample (sample ARE/L) in the same spatial volume ($z \leq 0.2$, $b \geq +30°$) which in addition to the clusters with spectroscopically measured redshifts contains also clusters with photometrically estimated redshifts for which there are no spectroscopic measurements so far. For this purpose we use the calibration equation

$$\log z \;=\; \underset{\pm 829}{-4.5372} + \underset{\pm\,50}{0.2132}\, m_{10}$$

from Kalinkov, Stavrev & Kuneva (1985), where m_{10} is the magnitude of the 10th brightest cluster member estimated by Abell (1958). Let us note that the photometrically estimated cluster redshifts may have large errors (20–30%). Sample ARE/L contains 1040 clusters.

3. ANALYSIS OF THE NUMBER DENSITY DISTRIBUTION OF CLUSTERS

Fig. 1 shows the variations of the spatial density of the number of clusters (in units $10^{-6}\ h^3\ \mathrm{Mpc}^{-3}$) as a function of the redshift for both analysed samples. The vertical lines in Fig. 1 correspond to the first four peaks in the number of galaxies discovered towards the North Galactic Pole by BEKS. The first two peaks are shown separately for the deep samples of galaxies (dotted line) and the bright samples (dashed-dotted line) used by BEKS (see their Fig. 1 a and b).

As it is seen in Fig. 1, the density distribution for the first sample AR/L (spectroscopically measured redshifts, solid line) fluctuates in the redshift range 0.01–0.09 around a mean level of about 6 $10^{-6}\ h^3\ \mathrm{Mpc}^{-3}$, i.e. in agreement with the estimate by Bahcall & Cen (1993) for the mean spatial density of the $R \geq 1$ Abell/ACO clusters. Therefore, we accept that sample AR/L is fairly complete for $z \leq 0.09$. In this range the spatial number density of clusters shows two well defined maxima at $z =$ 0.02–0.04 and $z =$ 0.07–0.08 which coincide well with the first two northern peaks in BEKS redshift distribution of galaxies, and correspond, as already pointed out in Sect. 1, to the Great Wall and to the Corona Borealis supercluster, respectively. In

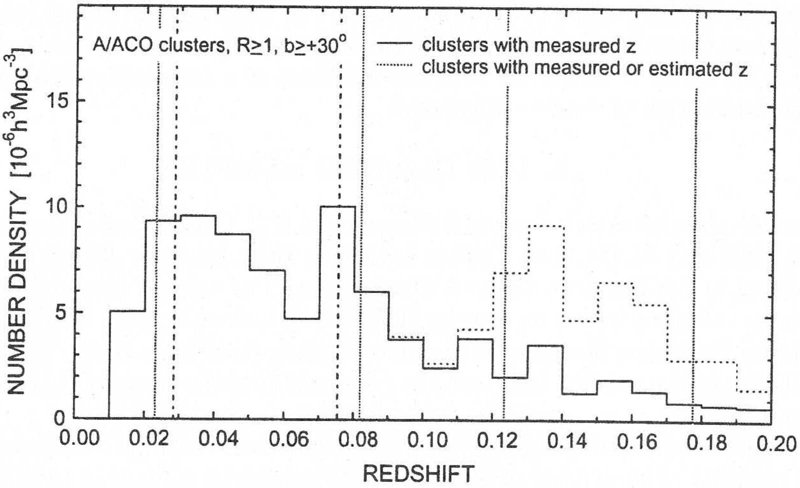


Fig. 1: Spatial number density of clusters as a function of redshift for Abell/ACO clusters of richness class $R \geq 1$ and galactic latitude $b \geq +30°$ (1) with measured redshifts (solid line), and (2) with measured or photometrically estimated redshifts (dashed line). The vertical lines correspond to the first four peaks in the number of galaxies discovered towards the North Galactic Pole by Broadhurst et al. (1990) according to the deep (dotted line) and bright (dashed-dotted line) galaxy samples used by them

the next redshift range, for $z = 0.09$–0.14, the number density of clusters with measured redshifts drops by about 50% because of the incompleteness of sample AR/L at larger distances. However, what makes impression is that the density in this range remains at the same mean level (although with some variations), showing no visible trend with the distance. For $z > 0.14$ the spatial density of clusters becomes very low due to the strong incompleteness of sample AR/L in this redshift range.

The number density distribution for the second sample ARE/L (measured or estimated redshifts, dashed line in Fig. 1) shows that the distribution function is identical with that for sample AR/L up to $z = 0.09$ and differs only slightly from it in the redshift range 0.09–0.12, while for $z > 0.12$ the difference is significant. As it is seen in Fig. 1, after the addition of the clusters with photometrically estimated redshifts a deep minimum in the number density of clusters is outlined at $z = 0.10$–0.11, followed by a high maximum for $z = 0.12$–0.14. This maximum coincides well with the third of the peaks in the number of galaxies in BEKS survey.

A similar strong density enhancement in the distance range 300–450 h^{-1} Mpc is known from the investigation of Scaramella et al. (1991) for a sample of rich ($R \geq 1$) Abell clusters, about 45% of which with estimated redshifts, and has been explained by these authors as an effect of the systematic overestimate of m_{10} for the distant clusters in Abell's catalogue. Such systematic errors do exist in this catalogue, as pointed out by Abell et al. (1989). However, in spite of the large errors introduced by the clusters with photometrically estimated redshifts the reality of the maximum at $z = 0.12$–0.14 cannot be definitely ruled out. An argument in support of this is the behaviour of the number density function for sample AR/L in the redshift range 0.09–0.14. As already pointed out, there is almost no decline in the density with redshift in this range. This fact can be easily explained if a real density enhancement of clusters at $z = 0.12$–0.14 is assumed. Another, independent argument is the peak in the number of galaxies at these redshifts detected by BEKS. Therefore, we suggest that the density maximum at $z = 0.12$–0.14 is a combined effect of (1) the systematic overestimate of m_{10} in Abell's catalogue, which has affected our photometrically estimated redshifts, and (2) the presence at that redshift range of a real giant 2-D structure similar to the Great Wall and the dominant planes and orthogonal structures suggested by Tully et al. (1992) and Einasto M. et al. (1997).

Let us also note that the fourth northern peak of BEKS shown in Fig. 1 at $z = 0.17$–0.18 probably indicates another giant structure more since it coincides by distance with the huge stratum composed of $R \geq 2$ Abell clusters discovered by Kopylov et al. (1988) in the redshift range 0.16–0.18.

If we accept that the Great Wall and the suggested three more distant giant structures are located at redshifts 0.02–0.03, 0.07–0.08, 0.12–0.14, and 0.16–0.18, respectively, then the quasi-regularity in the distribution of rich clusters is characterized by a period $\Delta z \sim 0.05$.

4. ANALYSIS OF THE SPATIAL VOID DISTRIBUTION

The samples AR/L and ARE/L (with somewhat modified limits: $b \geq +20°$, $z \leq 0.16$) have been used in Stavrev (2000) for identification of the large voids (diameter $D \geq 50\ h^{-1}$ Mpc) in the spatial distribution of galaxy clusters in a volume limited by galactic latitude $b \geq +30°$ and redshift $z \leq 0.14$ (distance $r \leq 420\ h^{-1}$ Mpc). (These limits concern the coordinates of the void centres.)

Fig. 2 shows cross-sections of the spatial distribution of the identified voids for both samples. A 3-D coordinate system centred in the Galaxy with axes x and y lying in the galactic plane and directed to points with galactic coordinates $l = 0°$, $b = 0°$ and $l = 90°$, $b = 0°$, respectively, and axis z directed to the North Galactic Pole, is used. Fig. 2 (a and b) present the two central cross-sections perpendicular to the galactic plane, along the x and y axes, respectively, for the voids in the distribution of the clusters from sample AR/L, and Fig. 2 (c and d) show the same but for sample ARE/L. Voids are marked with their serial numbers in the corresponding void catalogues described in Stavrev (2000). The cross-sections contain also the corresponding distributions of the clusters (filled circles) surrounding the voids (in slices 10 h^{-1} Mpc thick).

All cross-sections in Fig. 2 show that a large zone of enhanced number density of the clusters which is not intersected by large voids exists at a distance of 200–250 h^{-1} Mpc from the galactic plane. This zone is best outlined in Fig. 2 a and can be traced also in the adjacent cross-sections for $y \neq 0$ and $x \neq 0$ (not shown here). It is roughly parallel to the galactic plane (i.e. perpendicular to the supergalactic plane) with dimensions $\sim 300 \times 150\ h^{-1}$ Mpc along the x and y axes, respectively. This feature corresponds to the second maximum in the density distribution of Abell/ACO clusters at redshift $z = 0.07$–0.08 (see Fig. 1), as well as to the second northern peak in the number of galaxies in BEKS survey, and most probably indicates the presence of a giant 2-D structure similar to the Great Wall and to the giant structures suggested by Tully et al. (1992) and Einasto M. et al. (1997).

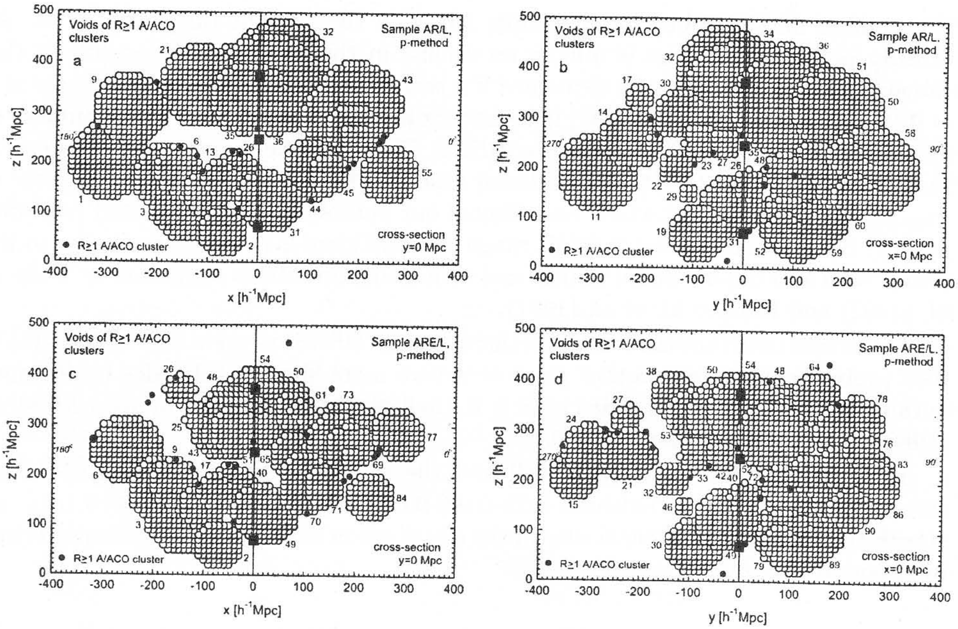
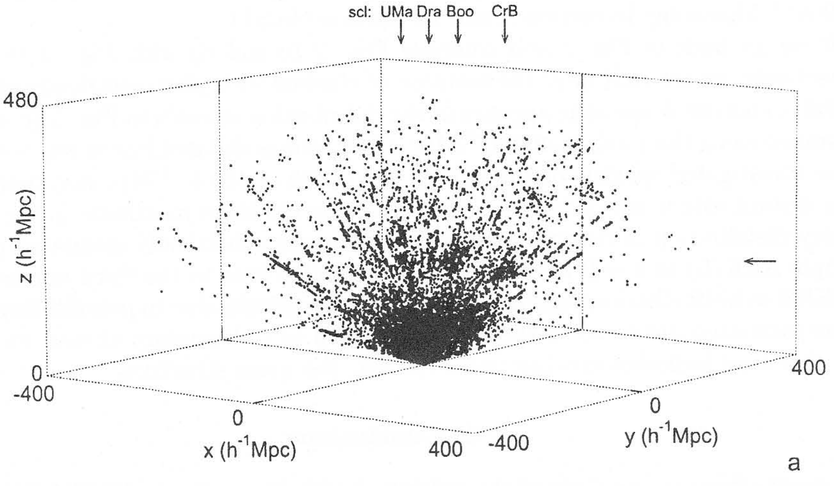
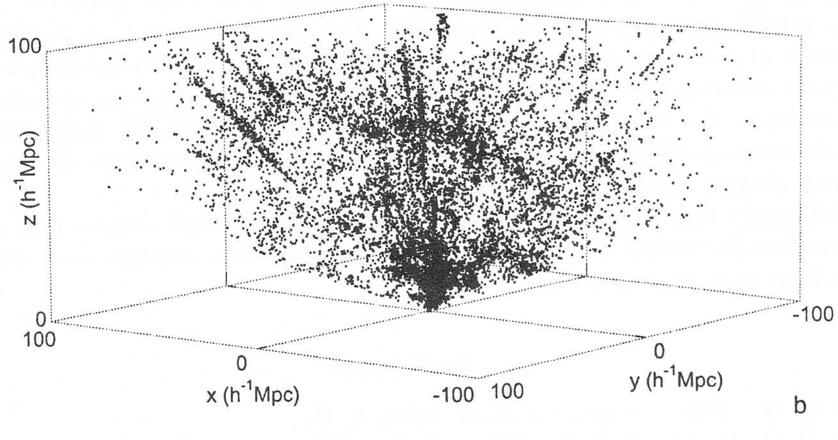


Fig. 2: Central cross-sections in the $x - z$ plane (left panel) and $y - z$ plane (right panel) of the spatial distribution of voids: a and b) voids of $R \geq 1$ Abell/ACO clusters with measured redshifts (sample AR/L), c and d) same as a and b but for clusters with measured or photometrically estimated redshifts (sample ARE/L). Voids are marked with their serial numbers from the corresponding void catalogues. The coordinate system is centred in the Galaxy with axes x and y directed to $l = 0°$, $b = 0°$ and $l = 90°$, $b = 0°$, respectively, and axis z directed to the North Galactic Pole. The distribution of clusters is shown by filled circles for slices 10 h^{-1} Mpc thick. The filled squares along the galactic axis correspond to the first three northern peaks in the redshift distribution of galaxies discovered by Broadhurst et al. (1990)

As we pointed out in Sect. 1, the second northern peak in the number of galaxies from BEKS survey was attributed by Bahcall (1991) most of all to the Corona Borealis supercluster. However, the dense zone which separates the large voids in Fig. 2 contains several more superclusters. We have identified this zone also in the spatial distribution of galaxies for a combined sample extracted from the Center for Astrophysics Redshift Catalogue (ZCAT, Huchra et al. 1992) and the MX Northern Abell Cluster Redshift Survey (Slinglend et al. 1998), shown in Fig. 3 for 19 879 galaxies in the Northern Galactic Hemisphere. A denser clumpy layer roughly parallel to the galactic plane can be seen in Fig. 3 a (shown by a horizontal arrow) at a distance $\sim$ 200–250 h^{-1} Mpc. It is composed of separate concentrations of galaxies elongated along the line-of-sight due to the finger-of-God effect. (Many of the "fingers" represent Abell clusters from the MX redshift survey.) These concentrations correspond (from left to right) to the Ursa Major, Draco, Boötes, and Corona Borealis superclusters (shown by vertical arrows). The layer borders on its nearest side with a less populated layer which contains the large void in Boötes.



Galaxies (b≥+20°, z≤0.16, n=19879)



Galaxies (b≥+20°, |x|, |y|, z ≤ 100 h^{-1}Mpc)

Fig. 3: Spatial distribution of the galaxies from the CfA Redshift Catalogue and the MX Northern Abell Cluster Redshift Survey, shown as perspective graphs with a coordinate system as in Fig. 2 for: a) 19 879 galaxies with galactic latitude $b \geq +20°$ and redshift $z \leq 0.16$, and a view point at $l \approx 320°$, $b \approx +18°$; the horizontal arrow and the vertical arrows show the positions of the superclusters in UMa, Dra, Boo, and CrB; b) galaxies to $|x|, |y|, z = 100\ h^{-1}$ Mpc and a view point at $l \approx 140°$, $b \approx +18°$

The distribution of galaxies in Fig. 3 b presents in more detail the nearer part of the distribution in Fig. 3 a (to 100 h^{-1} Mpc) seen from a view point opposite to that in Fig. 3 a. The Great Wall which corresponds to the first northern maximum in BEKS redshift distribution is well outlined as a giant flat structure at a distance $\sim 80\ h^{-1}$ Mpc roughly perpendicular to the line-of-sight.

If we go back to Fig. 2 and compare Fig. 2 (c and d) with Fig. 2 (a and b), respectively, we see that after the addition of clusters with photometrically estimated redshifts another dense zone appears in the distribution of voids in Fig. 2 (c and d) at a distance along the z axis $\sim 400\ h^{-1}$ Mpc. This zone is situated just at the boundaries of the investigated spatial volume limited to a depth of 420 h^{-1} Mpc and therefore its more distant side is not defined. It corresponds to the third maximum in the number density distribution of clusters with measured or photometrically estimated redshifts (sample ARE/L) at $z = 0.12$–0.14 (see Fig. 1) and is near to the third northern peak in BEKS redshift distribution. In spite of the uncertainties due to possible large errors in the estimated distances to the clusters, as well as to boundary effects, we suggest that this zone indicates another, more distant, flat giant structure.

5. Conclusions

The results from the analysis of the redshift distributions of rich Abell/ACO clusters in the Northern Galactic Hemisphere (Sect. 3), as well as of the spatial distribution of large voids of rich Abell/ACO clusters (Sect. 4), suggest the existence at redshifts 0.7–0.8 and 0.12–0.14 of giant two-dimensional structures, similar to the Great Wall and to the giant structures (dominant plane, orthogonal structures) suspected by Tully et al. (1992) and Einasto M. et al. (1997). The two structures have dimensions of the order of several hundred h^{-1} Mpc and are roughly parallel to the galactic plane. They are separated by large voids of rich clusters. This picture is in agreement with the existence of a large-scale regularity in the galaxy distribution, indicated by the one-dimensional BEKS survey, and is consistent with a quasi-periodic distribution of the rich clusters of galaxies with a period $\Delta z \sim 0.05$.

We expect that the results from the new extensive redshift surveys (2dF, SDSS) will confirm the reality of the two suggested extremely large structures and will throw more light upon their origin.

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