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Structure and dynamical state of two superclusters of galaxies

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Abstract. Using spectroscopic and CCD photometric observations on the 6 m and 1 m telescopes of SAO RAS the spatial structure of the apparently compact superclusters Ursa Major and Corona Borealis is determined. R_c-band Kormendy relation ($\mu_e = A \cdot \log(R_e) + C$) is employed for measurement of the relative distances of clusters along the line of sight.
The Ursa Major supercluster, having a velocity spread of 6000 km/s, on the whole obeys the Hubble dependence between radial velocity and distance, but is not a supermassive system with a large amount of "hidden" matter. Being stretched along the line of sight the supercluster consists possibly of two associations of clusters with mean velocities of 16200 and 19700 km/s. These subsystems are probably gravitationally bound with internal dynamical velocities not exceeding 1100 km/s.
Analysis of Hubble diagram of the Corona Borealis supercluster indicates that this system is one of rare in the present epoch extremely massive and dynamically active superclusters. It is likely that the compact core of the system, which is made up of five rich clusters, due to its high mass density has overcome the global expansion of the Universe and is in a stage of rapid gravitational collapse.

Key words: galaxies: clusters: general — galaxies: kinematics and dynamics

1. Introduction

Theory of formation of a large-scale structure as a result of gravitational instability predicts that on scales of 10–100 Mpc the inhomogeneities observed in the distribution of galaxies — superclusters and voids — must be at the linear stage of evolution of the density perturbations of matter. Typical peculiar velocities of galaxies and clusters of galaxies determined from the observations do not exceed 500–1000 km/s on these scales. One can expect greater velocities in rarely found compact and rich superclusters of galaxies. In the region of space with complete measurements of redshifts of clusters ($z < 0.08$) such systems number no more than 5–6. Nevertheless, compact superclusters apparently bring a main contribution to the effect of anisotropy (Bahcall et al., 1986) in the distribution of spatial orientation of pairs of clusters in the entire sample of nearby Abell clusters. An excess of pairs orientated along the line of sight may be caused by either the large peculiar velocities of clusters, about 1500 km/s, in massive dense superclusters with a large amount of "hidden" matter, or a purely geometrical reason — accidental orientation along the line of sight of a number of highly elongated superclusters. Analysis carried out by Bahcall et al. (1986) spoke out in favour of geometrical projection, while Rood (1992), on the basis of statistical estimates, came to a conclusion about the existence of large peculiar velocities in two most compact superclusters, Ursa Major and Corona Borealis.

To resolve this dilemma a straightforward determination of the extension of superclusters along the line of sight is needed, and for this it was necessary to determine the distances of individual clusters by a method which would be independent of the measurement of redshifts. A rather simple and effective way of solving this task, apparently, occurs by using bright galaxies of early morphological types which predominate in the central parts of clusters. For these galaxies the relation was established (Kormendy, 1977) between the effective radius and surface brightness on this radius, which can be measured comparatively easily by means of surface photometry, allowing one to determine the relative radial distances of clusters. This relation together with velocity dispersion of stars in a galaxy determine a so-called "Fundamental Plane", in which the scatter in the locations of early type galaxies is very small (Dressler et al., 1987; Djorgovski and Davis, 1987).

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2. Observational data

The Ursa Major supercluster at $z \simeq 0.06$ is a very compact group of clusters at least in projection onto the celestial sphere, consisting of eight Abell clusters and five additional clusters revealed by Baier (1980) (Anon1, Anon2, Anon3, Anon4) and Shectman (1985) (Sh166), which are of smaller but comparable richness as determined by Kopylov and Kopylova (2001). That these additional clusters belong to the supercluster was established by our measurements of radial velocities for several of galaxies in each of the clusters. Fig. 1 shows the arrangement of the clusters in the Ursa Major supercluster on the celestial sphere.

There are 107 galaxies in our catalog for Ursa Major for which spectroscopic and photometric observations were carried out on the 6 m and 1 m telescopes in 1991–1998. All the data and method of reduction are presented in a separate paper (Kopylova and Kopylov, 2001).

The Corona Borealis supercluster at $z \simeq 0.07$ is one of the most compact systems of clusters, and according to the supercluster catalog of Einasto et al. (1997) is made up of eight Abell clusters: A2019, A2061, A2065, A2067, A2079, A2089, A2092, and A2124. Postman et al. (1988) considered this supercluster to consist of six clusters, excluding A2019 and A2124. Fig. 2 shows the arrangement of the clusters in the Corona Borealis supercluster on the celestial sphere in equatorial coordinates.

Small et al. (1998) using a large number of galaxies with measured redshifts has determined the mass of the supercluster of $8 \cdot 10^{16} M_\odot$ with a help of numerical modeling of a supercluster with the same parameters as for Corona Borealis. They confirmed the conclusion of Postman et al. (1988) that the supercluster is gravitationally bound. Small et al. (1998) suggested that the system is in a dynamical phase of gravitational collapse. We demonstrated the validity of this proposal by using directly measured distances for clusters in the supercluster.

For the Corona Borealis supercluster most of CCD photometric observations were carried out on the 1 m telescope in 1996 (for details see Kopylova and Kopylov, 1998). With some additional data obtained in 1998 there are 95 galaxies in our catalog for this system.

3. Determination of distances

One of the main methods for determining the distances of galaxy clusters makes use of the physical properties of galaxies of early morphological type, E and SO, which dominate near the center of the clusters. We used the relation, first found by Kormendy (1977) and further denoted as KR, between the effective radius R_e (the radius enclosing half–light of the galaxy) and the effective surface brightness at this radius μ_e, in the form where the effective radius is given as a function of effective surface brightness:

$$\log(R_e) = A \cdot \mu_e + C. \tag{1}$$

The individual cluster zero points C can be used to determine relative distances. It is convenient to reduce the data to the comoving coordinate system by applying to the measured values cosmological corrections corresponding to individual distances of clusters. Relativistic effects and changes on the scale of the Universe contribute a correction $\delta\mu_e = 10\log(1 + z_{spec})$, where z_{spec} is the measured redshift which includes a peculiar (non-Hubble) velocity of the object. As z_{phot} we denote a redshift corresponding to the true cosmological distance. We applied the K correction in the form $\mathrm{K(z)}=1.1 \cdot z_{spec}$. The angular size of the effective radius r_e was converted to the linear size R_e (in kiloparsecs) for the "standard" cosmological model ($\mathrm{H_0} = 50\,\mathrm{km \cdot s^{-1} \cdot Mpc^{-1}}$, $q_0 = 0.5$).

Fig. 3 presents the Kormendy diagram for our combined sample of galaxies from Coma cluster, Ursa Major and Corona Borealis superclusters, and also 17 clusters (Kopylov and Kopylova, 1998) around the Giant Void: 434 E and S0 galaxies in total. Galaxies were usually chosen in the central zone of the cluster about 3 Mpc in size to a limiting absolute magnitude $M_R < -21.5$, so far as galaxies with $M_R > -21.5$ begin strongly deviate from the KR (Fig. 3).

In order to determine the relative distances of clusters we assume that the slope of KR is the same for all clusters. A forward linear regression gives

$$\mu_e = 2.437(\pm 0.054)\log(R_e) + 18.976(\pm 0.266), \tag{2}$$

and inverse regression equation is

$$\log(R_e) = 0.3468(\pm 0.008)\mu_e - 6.4588(\pm 0.100). \tag{3}$$

We use an averaging of forward and inverse regressions, which gives the mean scale $A = 0.3786$ and the zero point $C = -7.123$. For a sample of limiting magnitude $-21\overset{\mathrm{m}}{.}5$ a *rms* scatter of KR is equivalent to 24% uncertainty on a distance to a single galaxy.

If there is no deviation from the Hubble relation between velocity and distance for a cluster, i.e. $z_{spec} = z_{phot}$ or peculiar velocity is zero, the mean value of the free term in (1) for all galaxies in a cluster, $C_{cl} = < \log(R_e) - 0.3786\mu_e >$, should be the same as the average of all clusters (C_0), assuming that the net peculiar velocity of the whole sample is equal to zero. If z_{spec} includes a peculiar velocity, then a true photometric distance of cluster can be determined by the formula

$$z_{phot} = z_{spec} 10^{C_0 - C_{cl}}. \tag{4}$$

But the residuals of KR calculated as $\Delta\mathrm{KR}=\log(R_e) - 0.3786\mu_e + 7.123$ are correlated with the galaxy magnitude (as noted also by Gudehus

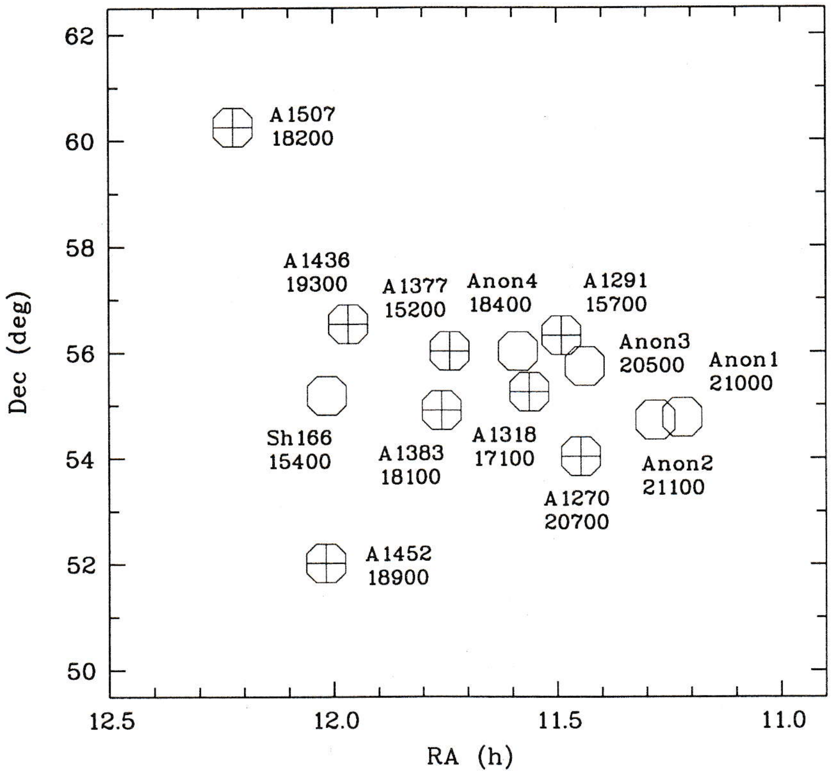

Figure 1: *The distribution of clusters in the Ursa Major supercluster in B1950 equatorial coordinates. A size of the region shown is* $\approx$ *75 × 75 Mpc for a middle velocity of the supercluster of 18400 km/s. A name and a mean radial velocity in km/s are given for each cluster. Clusters from the Abell catalog are shown by crossed circles.*

(1991) and Scodeggio et al. (1997)), and followed approximately a quadratic relation (Fig. 4). This fact makes distances derived by a simple KR extremely sensitive to the cluster population incompleteness. The effect is quite small for brighter galaxies (between -25^m and -23^m) but evidently should be taken into account for galaxies fainter than -23^m. By a least squares fit of a second-order polynomial to the Δ KR–M_R relation we have derived a correction equation in the form of $\Delta\mathrm{KR}=A_0 + A_1 M_R + A_2 M_R^2$, where $A_0 = -23.95, A_1 = -2.00, A_2 = -0.042$. It is shown in Fig. 4.

To reduce the systematic errors in determination of cluster distances, which are especially large in the case of inhomogeneous representation of bright and faint galaxies in different clusters, we added a correction Δ KR to the values of C (distances) for all galaxies. The mean errors in C_{cl} when averaging 4–14 galaxies in a cluster were 9% for Ursa Major and 6% for Corona Borealis without a correction and about 5% after applying of correction. Recalculating per one galaxy we obtain a 15% uncertanty in distance determination by the corrected KR.

4. Discussion and conclusions

Considering only the redshifts of clusters, it is impossible to unambiguously determine whether the extention of a supercluster along the line of sight, as derived from its spread of radial velocities, is real (the Hubble law is obeyed) or apparent (the system is in process of collapse and virialization that induces large peculiar velocities). The availability of distances to clusters measured photometrically makes it possible to determine spatial structure of the supercluster, draw the peculiar velocity field within its limits, and derive conclusions about the dynamical state of the system. Analysis of Hubble diagrams (Fig. 5 and Fig. 6) of two superclusters studied indicates a difference in the dynamical state of these systems.

The Ursa Major supercluster is looked as compact on a projection only. Radial distances of clusters correspond to their Hubble velocities on the whole (Fig. 5). The clusters are grouped into two associations with mean velocities of approximately 16200 and 19700 km/s. Difference of velocities gives a separation of 70 Mpc along the line of sight. Each of these subsystems may be gravitationally bound with internal dynamical (peculiar) velocities of about 1100 km/s.

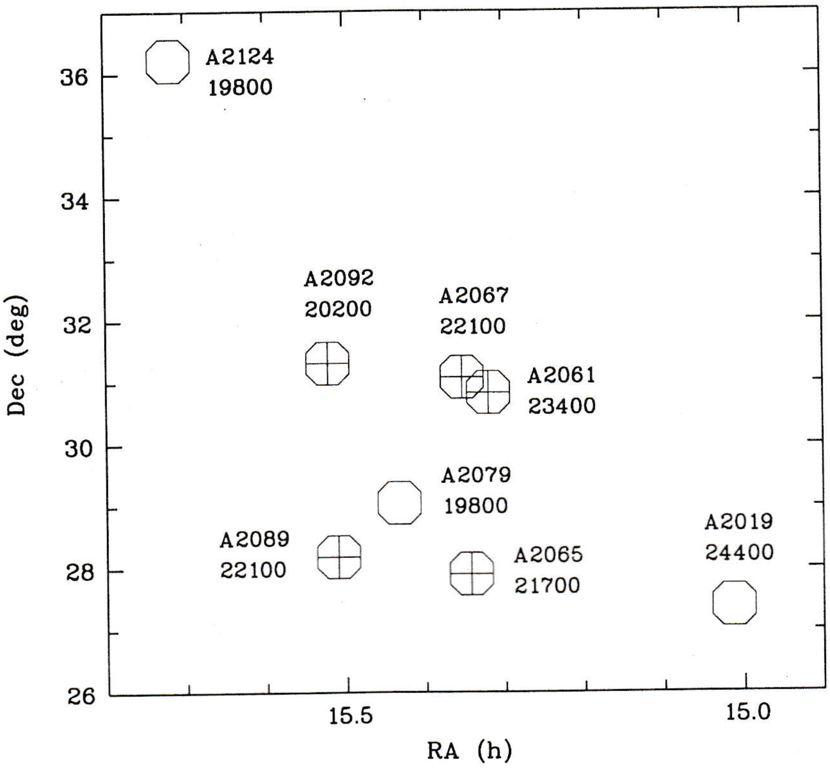

Figure 2: *The distribution of clusters in the Corona Borealis supercluster in B1950 equatorial coordinates. A size of the region shown is ≈ 75 × 75 Mpc for a middle velocity of the supercluster of 21700 km/s. A name and a mean radial velocity in km/s are given for each cluster. Clusters forming the core of the supercluster are marked by pluses.*

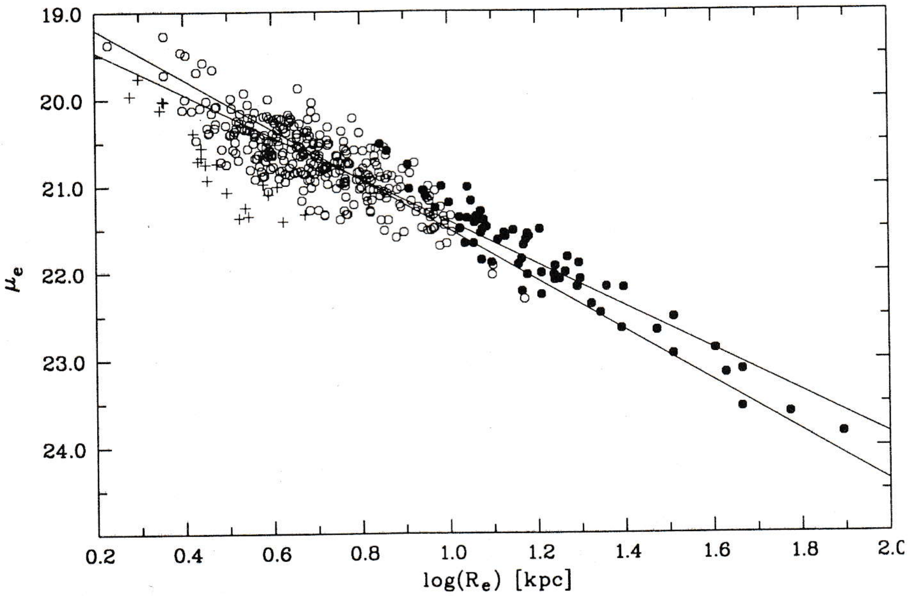

Figure 3: *The Kormendy relation for 434 early-type galaxies in 39 clusters subdivided into three magnitude-bins:* $M_R < -23^m.5$ *(filled circles),* $-21^m.5 < M_R < -23^m.5$ *(open circles),* $M_R > -21^m.5$ *(pluses). The lines are least-square fits with variables interchanged. A line with a steeper slope shows the inverse fit.*

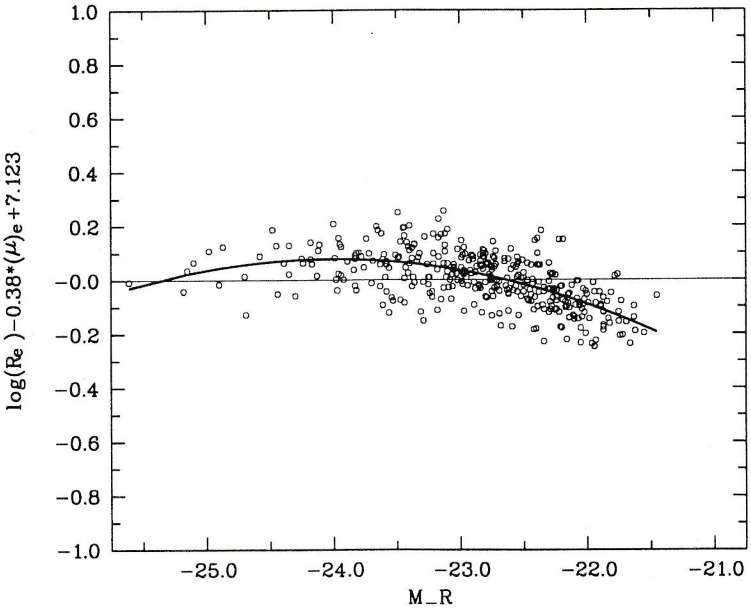

Figure 4: *The residuals for the Kormendy relation versus the galaxy luminosity. The thick line is the approximation curve:* $\Delta KR = 23.95 + 2.00 M_R + 0.042 M_R^2$.

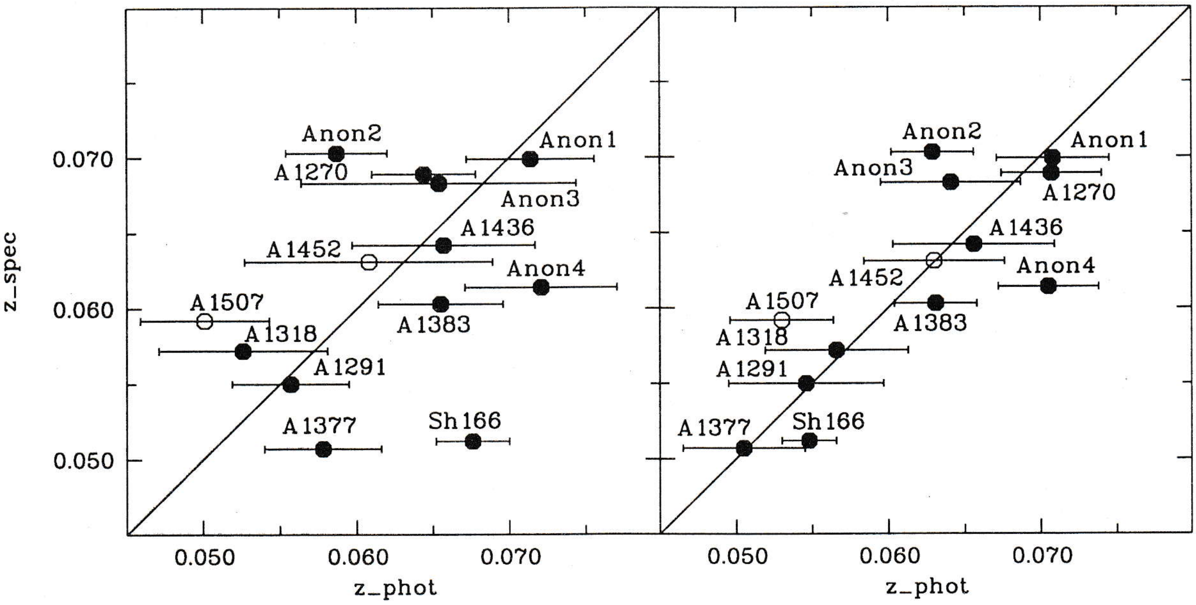

Figure 5: *The Hubble diagram of the Ursa Major supercluster for two variants: (left) without and (right) with applying a magnitude depended correction to distances of clusters. Two outlying (in projection on sky) members of the supercluster are shown by open circles.*

For the Corona Borealis supercluster (Fig. 6) it is evident that the Hubble law is not obeyed. We can clearly distinguish the core of the supercluster, formed of five (or six if A2019, most outlying in the sky projection, is also included) clusters, which display a dependence between velocity and distance that is characteristic for systems in a process of gravitational collapse. Cluster A2061 is closer than A2065 – the richest cluster of the supercluster approximately coincided with a centroid of the system – and has positive peculiar velocity, that is directed toward the centroid from the frontside of supercluster, while clusters A2089 and A2092 (further than A2065) have negative peculiar velocities, directed toward the centroid from the backside of the supercluster. A2079 and A2124 are obviously foreground clusters. Thus, the core of the Corona Borealis supercluster has overcome the global expansion of the Universe due to high mass density,

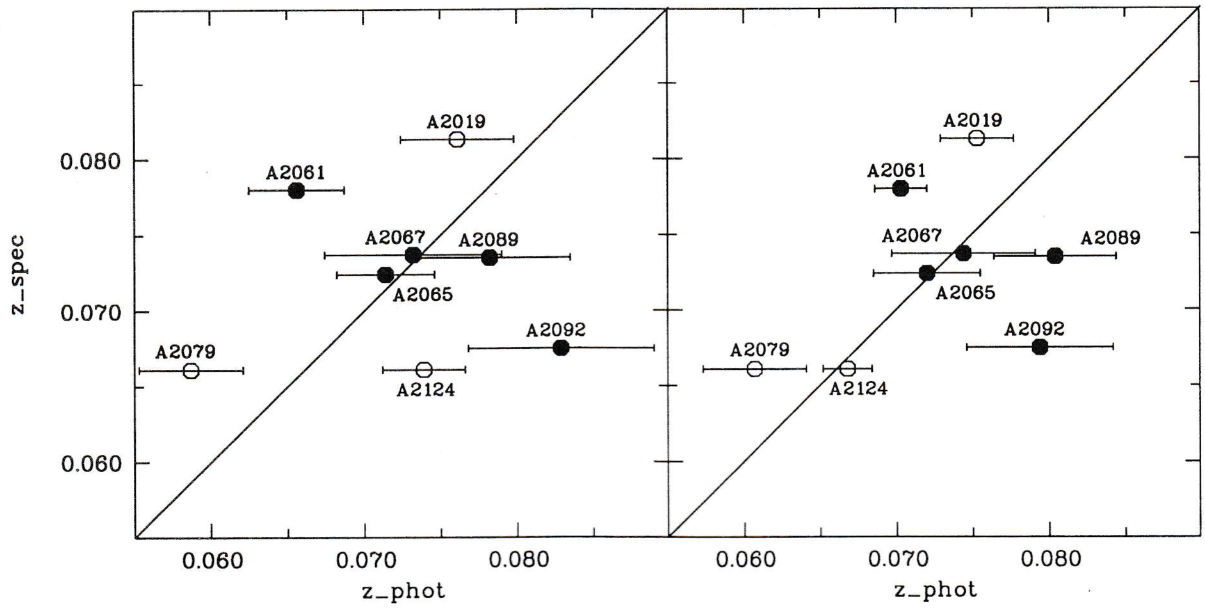

Figure 6: *The Hubble diagram of the Corona Borealis supercluster for two variants: (left) without and (right) with applying a magnitude depended correction to distances of clusters. The clusters forming the core of the supercluster are shown by the filled circles.*

and is in a stage of rapid gravitational collapse.

Our photometric cluster distance measurements have demonstrated that the Corona Borealis supercluster, and less probably two subsystems in the Ursa Major supercluster, are gravitationally bound and dynamically decoupled from the Hubble flow due to their high concentration of mass. At the current epoch in the evolution of the Universe, these systems probably represent the largest inhomogeneities in the large-scale mass distribution found on an initial stage of virialization. A detailed study of such systems would provide valuable information about the initial spectrum of inhomogeneities on scales of 10–100 Mpc and the relation between luminous and dark gravitating matter in the Universe.

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