KEYNOTE: STRUCTURE OF THE UNIVERSE

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A clear keynote for our conference is given by the diagram shown in Figure 1. This year we can celebrate that it is just half a century ago that it was produced by Harlow Shapley and Adelaide Ames. This marvellous picture illustrates nearly all we know about the properties of the Universe, except its expansion. It can teach us practically all the lessons we are still learning today. Most prominent is the Virgo cluster. Also evident are structures on larger scale, such as the appendages on both sides of the cluster, spanning a total length of 20 to 30 Mpc.* They are the kernel of the Local, or Virgo, supercluster. The supercluster has a complicated structure, evident from the clumpiness in the distribution along its axis, but likewise from the arrangement of the galaxies in its environment. The centre of the local supercluster (the Virgo cluster) lies at a distance of about 20 Mpc. The supercluster probably extends somewhat beyond us. However, everything in the Shapley-Ames picture should be considered as connected with this one supercluster. Features marked A, B and C may be independent structures; A lies at a distance of roughly 50 Mpc; C, at a distance of $\sim$ 70 Mpc, lies similarly well outside the Local Supercluster. The strongly elongated feature B, with an average velocity of 1400 km s^{-1} and a dispersion of only 300 km s^{-1}, appears also well isolated. All three are roughly 30 Mpc long, and may be considered as separate superclusters.

Look once more at the Figure. I want to comment on two other phenomena. The first: the occurrence of several large near-empty regions which cannot be ascribed to extinction in our Galaxy. To a certain extent the voids are a natural complement to the superclustering, but it is interesting to see the large contrast in density between "empty" and populated regions of space. The second phenomenon which I must refer to

*Throughout my lecture I shall use a Hubble constant of 50 km s^{-1} Mpc^{-1} for deriving distances and dimensions. Discussion of this constant is outside the programme of this symposium, and would be beyond the scope of my lecture. There are weighty reasons, principally based on the ages of globular clusters, to believe that H_0 lies between roughly 45 and 60 km s^{-1} Mpc^{-1}.

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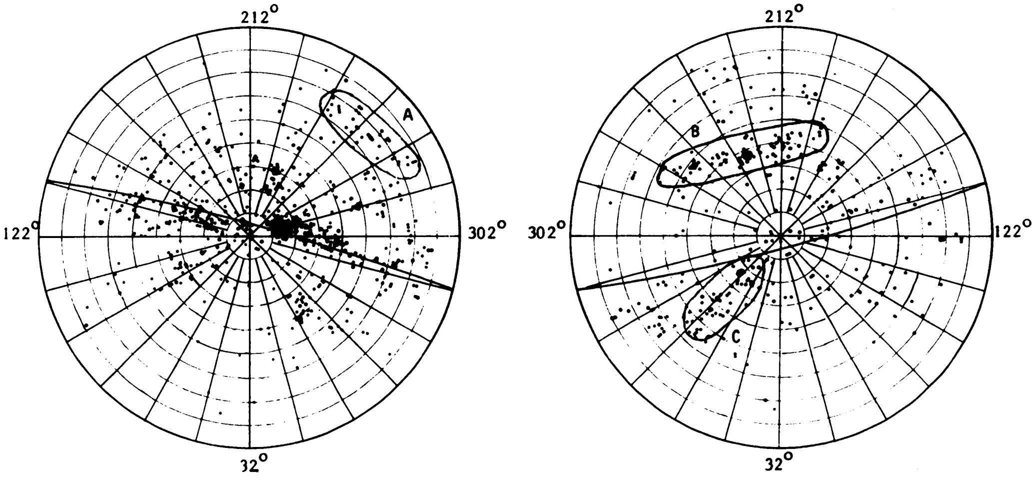

Figure 1. Distribution of galaxies brighter than the 13th magnitude in galactic coordinates; latitude circles are drawn every 10°. The north galactic hemisphere is on the left (Shapley & Ames 1938).

is the ever-present small-scale structure, the "clumping." The clumps come in all sizes: doubles, triples, multiples, small and large groups; they come also in different shapes, and seem to defy an encompassing description. However, some very useful characteristics have been brought out through a correlation description, worked out in great detail by Peebles. His two-point correlation, or covariance, function, $\xi(r)$, has over a large range of r the remarkably simple form $(r/r_o)^{-\gamma}$, with $\gamma = 1.8$; r_o, the "clustering length," is about 10 Mpc.

Perhaps the most interesting thing in the Shapley-Ames picture is the almost complete lack of equilibrium. Even the Virgo cluster itself, which is the only large feature showing signs of mixing, lacks the strong central concentration typical of a relaxed cluster. Every large feature in the picture appears cosmogonically young, and seems to bear the stamp of its origin. This impression is confirmed by the better insight afforded by the now almost complete radial velocity measurements: the smallness of the velocity dispersion indicates that the crossing times along the major axes of the Virgo supercluster are of the order of the age of the Universe, so that hardly any mixing can have occurred in these directions. It is only in the direction of the short axes that there are distinct signs of evolution. Similar conditions seem to hold for feature B, and possibly also for the two other superstructures, A and C.

For the small structures conditions are different. The "clumps" can all have been formed by gravitational clustering in an initially homogeneous Universe, provided that protogalaxies originated at a sufficiently early epoch. This has been shown convincingly by N-body simulations. Such simulations can reproduce in a striking manner the observerved covariance function. The marvellous outcome of these calcu-

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lations naturally prompts one to ask whether also the larger structures might be explained this way. On the basis of our present knowledge the answer must probably be "No, at least not _all_ such structures." In particular, it seems doubtful whether, starting from a random distribution, the strongly flattened, or elongated, shapes and the sometimes enormous dimensions can be produced that are characteristic of many superclusters. I mention, however, that interesting simulations have recently been made that _do_ produce supercluster-like formations, by choosing initial conditions in which fluctuations beneath a certain, rather large, scale are suppressed or by having galaxies formed at a very early epoch.

We have arrived here at one of the crucial questions for this symposium, viz., do the large structures we observe around us teach us something about the Universe before decoupling?

Before we can answer this question we must scrutinize more closely whether there is any possibility that structures of 50-100 Mpc, with the characteristics of superclusters, can have originated in the era _after_ decoupling. An original scenario has been suggested by Ostriker and Cowie. They considered the chain reaction which might be started by the blast waves in the intergalactic medium produced by the burst of radiation and supernovae expected to accompany the birth of a galaxy. The ensuing shocks may lead to the birth of other galaxies, and under suitable conditions might produce a chain reaction by which large, and possibly flat, structures could be built up. But it is still quite uncertain whether the process could lead to structures having such large dimensions as the largest superstructures that have been observed. Unsatisfactory aspects of the scenario are that it does not explain the origin of the seed galaxies from which the chain reactions must be started, and that, further, it is not clear how it could explain the apparent prevalence of elongated structures among the superclusters. A test of its applicability to superclusters might be obtained from a study of the systematic motions in their surroundings.

If the origin of the large superclusters has to be sought in the earlier Universe, it is evidently of very great interest to study their properties. Several communications will deal with observations tending to this purpose. The investigations made so far have indicated the following:

1. Superclusters fill perhaps 10% of the Universe; the space between them seems to contain comparatively little luminous matter. Most galaxy clusters, and the majority of galaxies, may belong to superclusters.
2. They show no signs of equilibrium or even mixing.
3. Traversal times along long axes are probably as long as the age of the Universe.
4. The largest dimensions reach up to about 100 Mpc, perhaps even 150 Mpc. There are indications that small-amplitude density fluctuations may exist up to 300 Mpc.
5. On scales beyond this the Universe appears essentially homogeneous.
6. The average separation between superclusters along a line of sight is of the order of 200 Mpc.

7. Mass estimates range from $\sim 10^{15}$ to perhaps 10^{17} $M_{\odot}$.
8. The majority of superclusters appears strongly elongated on the sky; many are probably elongated in space as well.
9. Some contain two or more "chains," at large angles to each other.
10. The major axes of rich clusters are -- at least in some cases -- aligned with the supercluster in which they are situated. The major axes of all rich clusters are strongly correlated with the direction toward the nearest neighbouring rich cluster, up to distances of 50-100 Mpc.
11. The orientation of double galaxies may be connected with that of the superstructure in which they lie.
12. In the outskirts of some superclusters indications of a deceleration of the Hubble expansion have been observed.
13. Superclusters may form a more or less connected cell structure, or network, throughout the Universe. This very important aspect, which was first suggested by Einasto, requires much more study.

In order that condensations be formed, the Universe must have carried within it deviations from homogeneity. The most massive structures probably existed before the decoupling of matter and radiation. In the so-called "adiabatic" theory, such structures should have had masses exceeding about 10^{14} $M_{\odot}$, smaller condensations having been destroyed by radiation drag in the fireball stage. It is interesting that all structures having the characteristics of superclusters (such as lack of equilibrium, or mixing, very long crossing times, and sizes such as could hardly have been produced in the time elapsed since the decoupling) appear to have just the sort of masses that could survive the radiation era.

In an alternative -- more controversial -- model of the Universe, the so-called isothermal model, fluctuations existed on all scales, and galaxies could presumably have begun to form soon after decoupling. The formation of clusters and superclusters would then have been non-dissipative; it could nevertheless have produced flat and oblong structures. It is evidently of interest to search for observational tests which can decide between the two models. A non-dissipative collapse cannot produce as steep a density gradient as a dissipative one. A close study of the galaxy distribution perpendicular to the long axes of edge-on, or cigar-like, superclusters might therefore provide such a test. Is, for instance, the steepness of the density drop toward positive supergalactic Z in Tully's Fig. 4 (Tully 1982) compatible with a non-dissipative formation?

Let us now consider the adiabatic picture. In this scenario clusters of galaxies, as well as detached galaxies, including quasars, would have formed only after the collapse of the superstructures. This should thus have taken place well before the birth of the oldest quasars, say at $z \sim 5$ or earlier. The well-known theory, that has been worked out so extensively by the Moscow school, is that at decoupling there were fluctuations of large scale, but small amplitude, in the universal medium, which at first expanded at the same rate as the Universe. The expansion of regions of excess density gradually lagged behind, and they finally collapsed. It was realized in an early stage, by Zeldovich and co-workers, as well as independently by Icke in Leiden, that unless the shapes of the fluctuations would have been implausibly close to spheres they would always collapse first along their smaller diameters, and form either "pancakes," "cigars," or more complicated structures. This yielded a natural explanation of some of the striking properties of superclusters.

What amplitudes must the initial fluctuations (at z = 1000) have had in order to collapse at z = 3, corresponding to an age of 1.63 x 10^9 years in an Einstein-de Sitter Universe, or 3.45 x 10^9 years in a Universe with $\Omega = \rho/\rho_{crit} = 0.1$? For a spherical fluctuation we have the following simple relation between the fractional density excess η at z = 1000 above the average density in an Einstein-de Sitter Universe, and the time of collapse t in units of 10^9 years: $t = 0.00019\ \eta^{-3/2}$. For the Einstein-de Sitter case this gives $\eta = 0.011$; for the open Universe $\eta = 0.007$. In the latter case the excess over the mean density in the Universe considered would be 0.016. For a collapse at z = 10 instead of 3, the density excesses should have been 0.030 and 0.025 for the two cases respectively.

Fluctuations with amplitudes as large as these are improbable on theoretical grounds. Expected amplitudes for supercluster masses are an order of magnitude smaller. The amplitudes quoted are likewise excluded by observations of the background radiation. A mass of 10^{16} $M_\odot$ subtends at z = 1000 an angle of 19!2 in an Einstein-de Sitter Universe, and 4!85 in a Universe with $\Omega = 0.1$. On such scales upper limits of roughly 0.0004 have been found for fluctuations in the background radiation, again much smaller than the figures given above.

There may be various ways out of this apparent discrepancy. One such way is to assume that the initial fluctuations deviated considerably from a spherical shape. The collapse times along the short axes can then be substantially shortened, while the structures continue to expand along their long axes. The collapse times can further be reduced by the "overshoot" mechanism suggested by the Soviet astronomers. An earlier collapse could also occur if the greater part of the density consists of particles such as heavy neutrinos that decoupled from radiation at a much earlier epoch. Small density fluctuations in the neutrino gas could then recollapse at an earlier time, and form potential wells in which baryons would collect. A combination of these various possibilities may have led to a sufficiently early formation of the Zeldovich "pancakes" (between about z = 5 and 10) without requiring fluctuations in the cosmic background temperature that conflict with observations.

It is evidently worth a great effort to obtain more accurate measurements on the fluctuation of the background on scales from 2 to 20'. Expected amplitudes of fluctuations corresponding to protosuperclusters are not very far below the upper limits already established. Discovery of these fluctuations, and determination of their brightness, diameters and shapes, might be the greatest contribution to cosmology that can presently be made.

REFERENCES

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Tully, R.B.: 1982, Ap. J. 257, p. 389.

DISCUSSION

Inagaki: Are superclusters joined together, or isolated from one another?

Oort: In some cases superclusters seem to be interconnected, but more redshifts are required before such connections can definitely be outlined. It is unknown whether there are superclusters which are truly isolated.

Miller: What is the distinction between clusters and superclusters? Is the distinction clearly defined observationally? Are clusters anything more than irregularities along a supercluster chain or blobs at the junction of two or more chains?

Oort: A rich cluster is usually fairly well defined and distinguished from the surrounding supercluster (if it lies in a supercluster). A useful distinction between clusters and superclusters is that the first are generally relaxed, while the second are not. The Virgo cluster is an intermediate case: reasonably well-mixed, but lacking the central concentration of an equilibrium structure.