The Texture of the Universe[a]

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You ain't seen nothin' yet. (Al Jolson)

Just as the texture of an antique fabric is the result of the vanished loom that made it, the present texture of the universe is a result of physical processes operating in a distant and inaccessible epoch. An adequate justification for detailed study of the three-dimensional distribution of galaxies would be to derive an accurate description of the ways galaxies cluster. Yet the value of this work is greatly enriched by the prospect that studies of today's galaxies may reveal important properties of conditions arising from a hot big bang. No one doubts (except Ostriker and Cowie)[16] that the principal mechanism for forming galaxies and galaxy clusters is gravitational instability. Evolution from very large structures (10^{15} $M_\odot$) *down* to galaxy sizes is favored in the picture advocated by Zeldovich and his collaborators,[20] while the assembly of large structures from smaller ones characterizes the clustering picture described by Peebles.[17] Looking for structure, both density enhancements and voids in the galaxy distribution, on large scales (of order 50 h^{-1} Mpc), may provide important clues on the fossilized structure derived from primeval galaxy evolution.

One approach to studying the large-scale structure is to examine in detail the largest nearby structure: the local supercluster. Assembling the nearby structure requires accurate distance measures to individual galaxies. During the past decades, this work has been carried forward by de Vaucouleurs[3,4] and has recently been

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described in great detail by Tully, who concludes that the structure of the local supercluster is extremely stringy and inhomogeneous on scales of a few megaparsecs.[19] Evocative, but much less detailed, studies of distant superclusters by Joeveer, Einasto, and Tago and Einasto, Joeveer, and Saar have suggested similar properties on much larger scales.[10,5]

Red shifts provide the evidence for the most convincing investigations of the three-dimensional structure of galaxy distributions on scales of 10 h^{-1} Mpc or more. Ignoring the possible effects of velocity fields (which can be assessed separately), the measurement of a galaxy's red shift to an accuracy of 100 km s^{-1} provides its distance to a precision of 1 h^{-1} Mpc. Surveys of galaxy red shifts by Gregory *et al.* start in the vicinity of well-known density enhancements, such as nearby dense clusters of galaxies, and then trace the extent of the dense region.[7,8] These surveys show that filaments of galaxies stretch over tens of degrees from the dense cluster core, corresponding to 20–30 h^{-1} Mpc. Intervening volumes often show large regions of low galaxy density. Long, stringy density enhancements extending over a radian on the sky at a distance of 40–53 h^{-1} Mpc, but with a width of only 2°, have been identified from a red shift survey by Giovanelli and Haynes.[6]

Large-scale inhomogeneity has also been revealed from the thorough red shift survey carried out at the Harvard-Smithsonian Center for Astrophysics by Davis *et al.*[2] Their survey, which includes 2,400 galaxies with red shifts averaging about 5,000 km s^{-1} (distances of 50 h^{-1} Mpc), reveals a "frothy" structure of dense strings and voids on scales of tens of megaparsecs. Having a large sample, as in the CFA survey, allows a detailed comparison with N-body simulations of galaxy clustering.

In order to study the structure of galaxy clustering on still larger scales, a significantly fainter (hence deeper) sample is required. Narrower fields, but greater depth, in a complete red shift survey provide the data for evaluating the luminosity function for galaxies, and the mean luminosity density. Kirshner, Oemler, and Schechter carried out a red shift survey to an average depth of about 10,000 km s^{-1} (100 h^{-1} Mpc),[11,12] but found that the study of average properties was hampered by fluctuations in the space density of galaxies by a factor of 3 on scales of roughly 50 Mpc. Our attention then shifted to the clustering properties. Fluctuations on scales of 50 Mpc demanded a survey of even greater depth, which we carried out in six fields, three in the north galactic cap and three in the south of 2 square degrees each, to an apparent magnitude of 17.5. Yielding 280 red shifts with an average depth of 200 h^{-1} Mpc, this survey provided data for an evaluation of the luminosity function and luminosity density for a fair sample of the universe.[14] Our attention, however, centered on a peculiar feature in the northern fields of the survey. Unlike the southern portion, the north showed a large enhancement of galaxy density at a red shift of 10,000 km s^{-1} (100 h^{-1} Mpc) and at a red shift near 22,000 km s^{-1} (220 h^{-1} Mpc), with a vast region 6,000 km s^{-1} across centered at 15,000 km s^{-1} which contained only 1 galaxy where about 20 had been expected.[13] Bravely asserting that this large (10^6 Mpc^3 for $H = 50$), low-density region, seen in each of the three northern fields separated by about 35° on the sky, was present in the triangle that they bound, we dubbed this region the Boötes void.

Extension of the survey to the interior of the triangle, as illustrated in FIGURE 1a, has now been carried out.[15] We have constructed a magnitude-limited sample in 282 small fields, each 15′ on a side, placed on a grid that covers the triangle formed by the original three fields. Extending from the center of the proposed void (at $\alpha = 14^h\,40^m$, $\delta = +50$) we doubled the density of our survey fields. Large gaps in the galaxy distribution at the location of the proposed void are apparent from comparing FIGURES 1b, 1c, and 1d, which use the radial velocities measured for 231 galaxies in the 282 fields. Low-velocity galaxies, in the range 6,000 to 12,000 km s^{-1}, are distributed over all the survey fields as shown in FIGURE 1b. More distant galaxies, in the range 18,000 to 24,000 km s^{-1}, have a similar distribution shown in FIGURE 1d. And in the range 12,000 to 18,000 km s^{-1}, the proposed void, we observe a conspicuous absence of galaxies just where the density of survey fields is highest. Knowledge of the three-

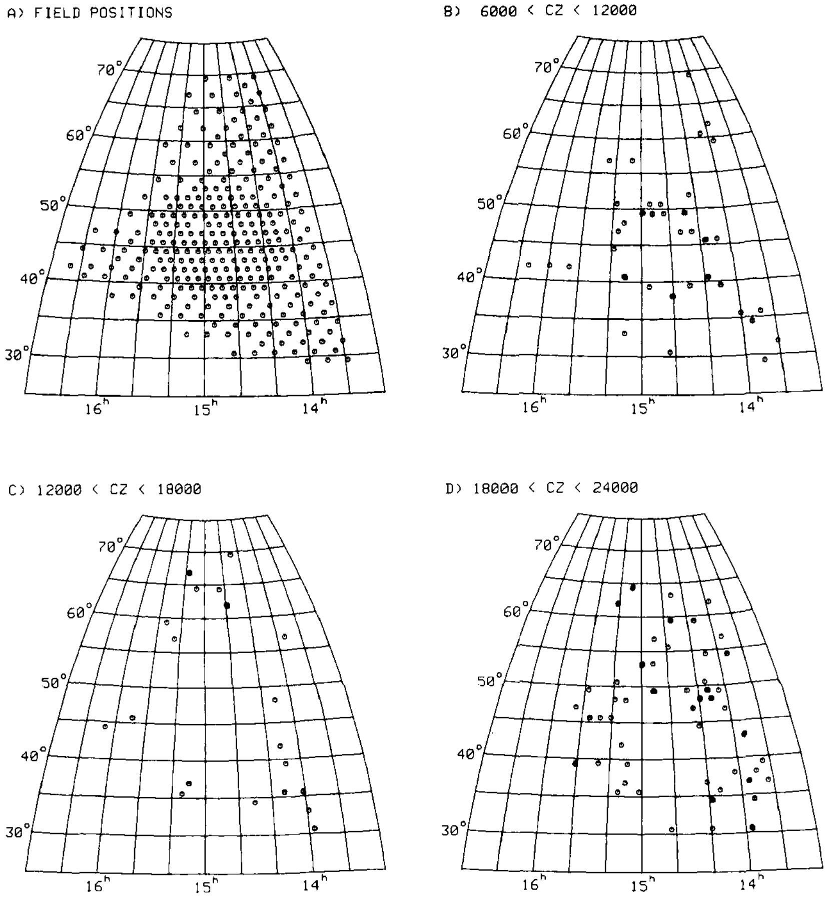

FIGURE 1. (A) Distribution on the sky of 282 sample fields. (B) Galaxies with red shifts between 6,000 and 12,000 km s^{-1}. (C) Galaxies with red shifts between 12,000 and 18,000 km s^{-1}. (D) Galaxies with red shifts between 18,000 and 24,000 km s^{-1}.

dimensional positions shows that a sphere at $\alpha = 14^h\,48^m$, $\delta = +47$ with a diameter of 6,000 km s^{-1} contains no galaxies from this sample.

Emission-line galaxies in the direction of the void have been investigated by Balzano and Weedman,[1] who found that some Markarian galaxies are within the triangle bounded by the original three fields, but detailed study shows none in the 6,000 km s^{-1} sphere. More emission-line galaxies in the Boötes region were detected in a survey by Sanduleak and Pesch,[18] but red shift measures by Gregory *et al.* show that these galaxies are not in the volume of the void.[9] Of course, surveys of emission-line objects may eventually prove useful for delineating the large-scale distribution of galaxies, because it is so easy to measure their red shifts. However it is important to establish whether galaxies with emission lines provide a reliable tracer of the overall galaxy distribution.

Very crudely, we estimate that there is a 90% chance that the density of the Boötes void is at least four times lower than the average in this survey. It is worth recalling that this survey shows that the region in Boötes is missing bright galaxies comparable to M31 or the Milky Way, but it does not demonstrate that the region has a corresponding mass fluctuation. Evenly distributed matter (such as the many -inos emitted by theoretical physicists) or low-luminosity galaxies are not excluded. Still, this investigation shows that the study of holeography may provide useful constraints on models of galaxy formation.

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