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SPACE DISTRIBUTION OF Sc GALAXIES: CLUES TO THE LARGE-SCALE STRUCTURE

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ABSTRACT

The redshifts (in units of 100 km s^{-1}) of the homogeneous sample of Sc I–Sc II galaxies with m_p = 14.0–15.0 mag obtained by Rubin *et al.* are placed at their galactic locations on an equal-area projection of the celestial sphere. This "redshift map" and auxiliary maps with narrower "redshift windows" illustrate the existence of the Hydra/Centaurus and Hercules/A2199 superclusters. They also reveal that the Coma cluster is part of a structure which includes not only A1367 but A779 as well, and may extend more than 200 Mpc across the celestial sphere. Similarly, the Perseus chain of clusters is part of a structure which fills a large fraction or all of the sky. By examining the redshift maps, one could gain the impression that the universe is an irregular three-dimensional "net"—chains and clumps of galaxies separating vast voids.

Subject headings: galaxies: clusters of — galaxies: redshifts

I. INTRODUCTION

By analyzing the projected distribution of galaxies on the celestial sphere, Peebles *et al.* (see Peebles 1974) found large-scale clustering and superclustering. Direct detection of superclusters with characteristic sizes ~40 Mpc (herein H = 50 km s^{-1} Mpc^{-1}) in relatively narrow cones of three-dimensional space came from the statistically homogeneous redshift surveys by Chincarini and Rood (1972, 1975, 1976), Tifft and Gregory (1976), and Gregory and Thompson (1978) (Coma or Coma/A1367 supercluster); Tifft and Gregory (1977) and Gregory, Thompson, and Tifft (1979) (Perseus or A426/A347/A262/NGC 507/NGC 383 supercluster); and Tarenghi *et al.* (1977) (Hercules or Hercules/A2199 supercluster). These studies also revealed the existence of vast, apparently vacant "voids" in the universe. The sizes of these voids are typically comparable to the sizes of the superclusters. Joeveer, Einasto, and Tago (1977) attempted to derive the all-sky three-dimensional distribution of galaxies from the redshift data in the *Second Reference Catalogue of Bright Galaxies* (RC2, de Vaucouleurs, de Vaucouleurs, and Corwin 1976). They independently discovered the Perseus supercluster and concluded that the three-dimensional distribution of galaxies resembles cells: galaxies and clusters of galaxies are concentrated toward cell walls enclosing voids of a very low spatial density of galaxies. The quantitative statistical reality of these voids was deduced by Chincarini (1978), who concluded, in agreement with Soneira and Peebles (1977), that if a field component does exist, it amounts to substantially less than 15% in a catalog selected by apparent magnitude.

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The above studies constituted a significant advance in our understanding of the three-dimensional structure of the universe. But they are also somewhat limited. (i) Studies of surface distributions cannot recover the full detail of three-dimensional distributions. (ii) It is not possible to fully recover the broad-scale structure of the universe from views of a few narrow cones. (iii) The all-sky view obtained from the RC2 is distorted by the inhomogeneity of the data, which reflects the specific research interests of observers.

To derive the three-dimensional structure of a cosmologically significant sample of the universe, a complete all-sky redshift survey of all galaxies brighter than some faint apparent magnitude limit is desirable. This task requires many years of work. In the meantime, an improved view of the universe would be provided by a homogeneous all-sky redshift survey of a specific type of galaxy in a chosen apparent magnitude window. Such a survey already exists. Rubin *et al.* (1976) have derived redshifts for a large sample of Sc I–Sc II galaxies in the Zwicky magnitude range ~14.0–15.0 mag. Although the sample is more complete for the northern than for the southern hemisphere, it was selected to provide good sky coverage, so that sparsely populated regions were sampled completely but only representative samples from denser regions were chosen. Therefore, the Rubin *et al.* (1976) sample provides a more homogeneous picture of the universe than actually exists: any clumps of galaxies in the observed sample should be even more prominent in actual space, and any large voids observed in the galaxy distribution should be real. The purpose of this paper is to communicate what we have learned about the structure of the universe by examining the Rubin *et al.* (1976) data.

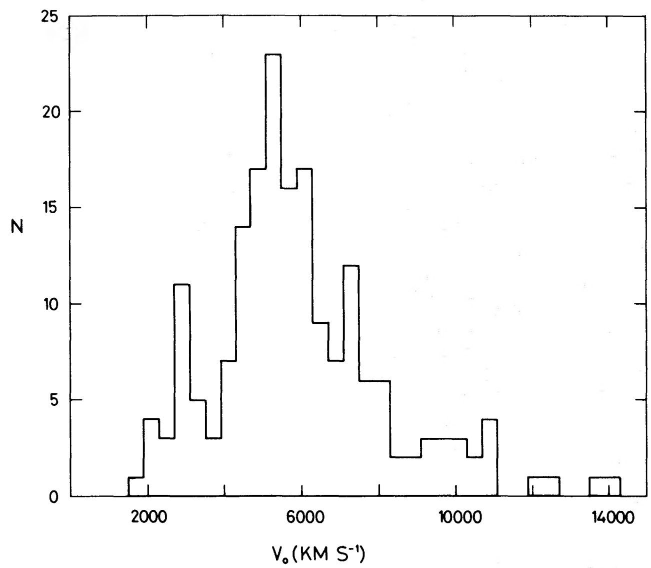

FIG. 1a

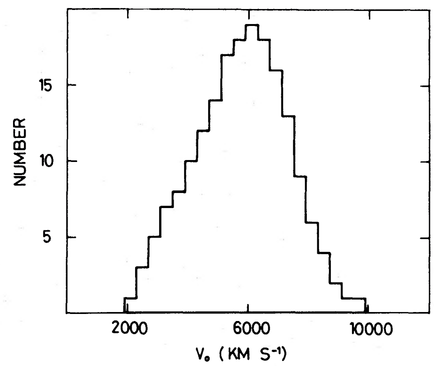

FIG. 1b

FIG. 1.—(*a*) Frequency distribution of all redshifts in the Rubin *et al.* (1976) sample. (*b*) Theoretical frequency distribution for uniformly distributed galaxies, the bin size equal to that of Fig. 1*a*.

II. RESULTS AND DISCUSSION

Figure 1*a* is the observed frequency distribution of radial velocities (V_0, relative to the Local Group) of the galaxies in the Rubin *et al.* (1976) sample. If the galaxies were ideal "standard candles" with absolute magnitude $M_0 = -21.24$ mag (Rubin *et al.* 1976), then only those which lie between 4200 and 6700 km s^{-1} would be in the 1 mag apparent magnitude observing window. Galaxies are also observed outside this redshift range, principally because there is a dispersion $\sigma_M \approx 0.3$ mag about M_0 (Rubin *et al.* 1976). Under the assumptions of a uniform spatial distribution of galaxies with a Gaussian luminosity function and moving in the Hubble flow, the number of galaxies in the solid angle $\Delta\Omega$ within the range of radial velocities (V_1, V_2) is

$$N(V_1, V_2) = \Delta\Omega \int_{V_1/H}^{V_2/H} x^2\Phi(x)dx ,$$

where $x = V/H$ and

$$\Phi(x) = \frac{A}{(2\pi)^{1/2}\sigma_M} \int_{M_1}^{M_2} \exp\left[-(M - M_0)^2/2\sigma_M{}^2\right]dM ,$$

where A is the total number of galaxies in the Rubin *et al.* sample, $M = m - 25 - 5 \log(x/\text{Mpc})$, and M_1 and M_2 are the absolute magnitude limits corresponding to the apparent magnitude limits of the Rubin *et al.* sample. The derived theoretical distribution is presented in Figure 1*b*.

Whereas the theoretical histogram (Fig. 1*b*) is "smooth," the observed histogram (Fig. 1*a*) contains suggestions of prominent "peaks"—preferred redshifts—at 2900, 5300, 7300, and 10,900 km s^{-1}. The observed and theoretical distributions differ with greater than a 99.5% probability, according to a χ^2 test. The latter three values are remarkably close to the mean redshifts of the Perseus, Coma, and Hercules/A2199 superclusters, respectively. To further understand the nature of these features, we construct "redshift maps" (Chincarini and Rood 1971; Tifft and Gregory 1976) from the Rubin *et al.* (1976) data. Figure 2 presents the redshifts (in units of 100 km s^{-1}) of the Rubin *et al.* galaxies at their Galactic latitudes (b) and longitudes (l) on an equal-area projection of the celestial sphere. Few galaxies lie in the "zone of avoidance" at $-10° \leq b \leq 10°$. The curve in the lower-left section of the projection encloses the region with declination less than $-45°$, where the Rubin *et al.* sample is especially incomplete. Galaxies cover the remaining area, but there appear to be large-scale structural formations and vast voids. The region surrounding $l \approx 285°$, $b \approx 25°$ contains numerous galaxies with redshifts near the "2900 km s^{-1} peak" value. To see this more clearly, we present in Figure 3 a redshift map for the galaxies with 2200 km s^{-1} $\leq V_0 \leq$ 3600 km s^{-1}, that is, those which lie within $\pm$700 km s^{-1} of 2900 km s^{-1}. Although these galaxies are scattered over the celestial sphere, a prominent clump—a "supercluster"—of galaxies is evident near $l \approx 285°$, $b \approx 25°$. Since this position is in the southern hemisphere, we checked to see whether any southern groups listed by Sandage (1975) are located there. We found, in fact, that eight of the ~20 tabulated groups congregate in that region (Table 1). Since the A1060 = Hydra I and the Centaurus clusters are the richest of the eight groups, we evidently discovered the Hydra/Centaurus supercluster. This structure extends ~90 × ~20 Mpc across the celestial sphere and has a radial

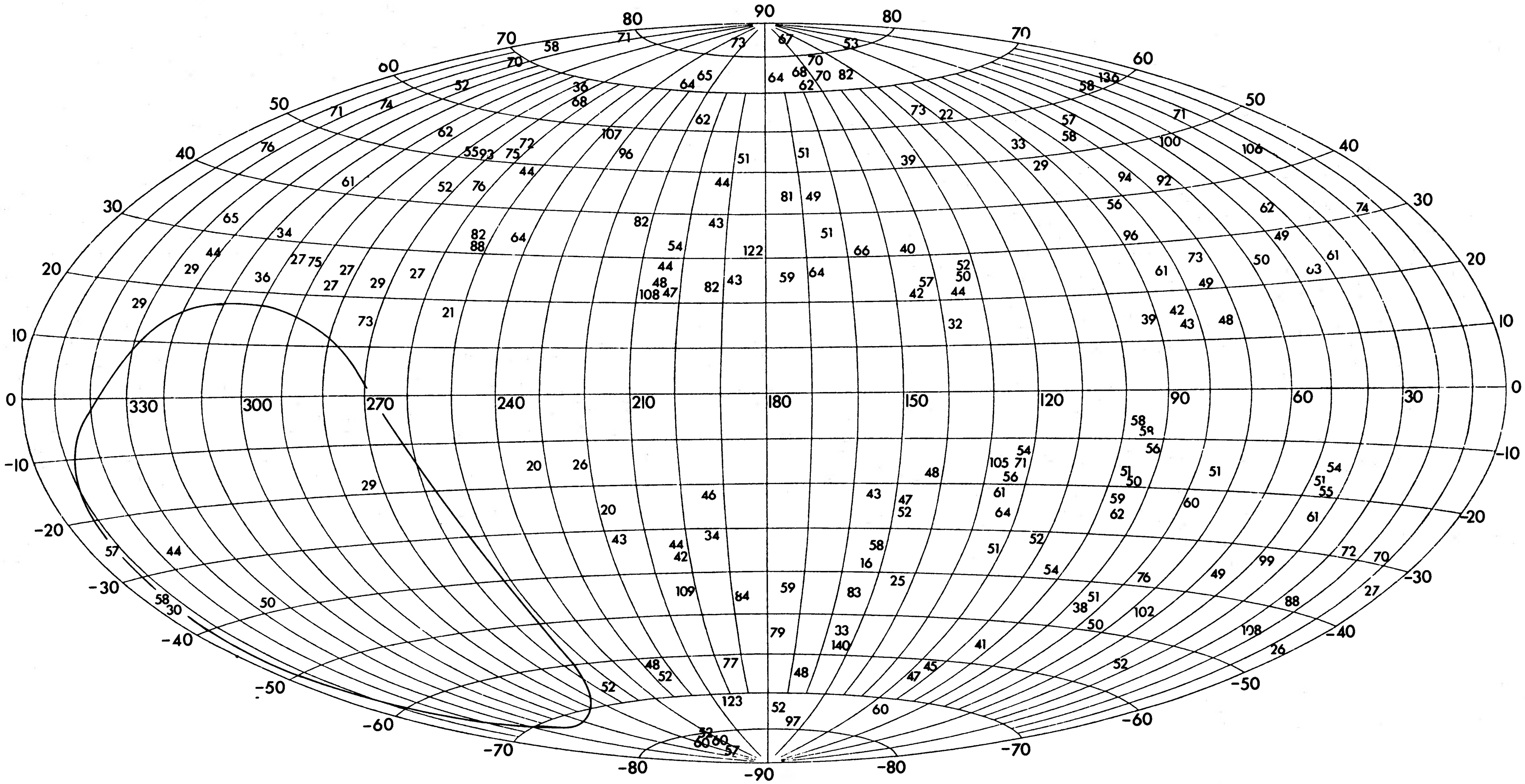

FIG. 2.—Redshifts (in units of 100 km s^{-1}) of all galaxies in the Rubin *et al.* (1976) sample placed at their galactic locations on an equal-area projection of the celestial sphere. The angular coordinates of this "redshift map" are Galactic latitude (b) and Galactic longitude (l). Note the "zone of avoidance" at $-10° \lesssim b \lesssim 10°$. The curve in the lower-left section of the projection encloses the region with declination less than $-45°$.

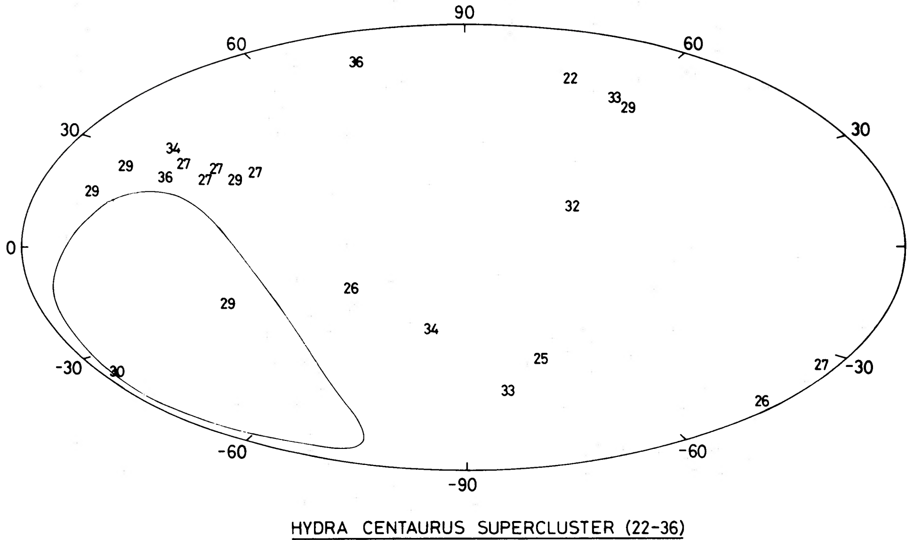

FIG. 3.—Redshift map for the galaxies with 2200 km s^{-1} $\leq V_0 \leq$ 3600 km s^{-1} in the Rubin *et al.* (1976) sample. See legend to Fig. 2 for further details.

depth of ~35 Mpc (difference between the redshifts of the nearest and farthest group member).

Fall and Jones (1976) have pointed out a correspondence between the locations of nearby Abell clusters and the Rubin *et al.* (1976) galaxies. Figure 4 is a redshift map of the clusters in Abell's (1958) distance classes 0, 1, and 2 (Table 2). The most compact groups of clusters represented in this figure were noted by Rood (1976). Examples of such prominent groups are A2199/A2197 and A2151/A2152/A2147. Abell (1961) believes that these groups plus the cluster A2162 (which lies between them) constitute a common supercluster (which we call the Hercules/A2199 supercluster). Tarenghi *et al.* (1977) find support for this interpretation from the redshift data in the RC2. Figure 5 is a redshift map of the Rubin *et al.* (1976) galaxies with 8600 km s^{-1} $\leq V_0 \leq$ 11,700 km s^{-1}, which bounds the redshifts of the clusters in Abell's proposed supercluster. There is indeed a clump of Sc I–Sc II galaxies at the location of the Hercules/A2199 supercluster, which lends further support to the reality of its existence. The Hercules/A2199 supercluster extends ~90 × ~50 Mpc across the sky, and its radial depth at the location of the A2151/A2152/A2147 group is ~100 Mpc (Tarenghi *et al.* 1977). Figure 5 also shows the presence of additional Sc I–Sc II galaxies in the 8600–11,700 km s^{-1} window scattered rather irregularly across the sky.

Gregory and Thompson (1978) observed the connection between the Coma supercluster and the cluster

TABLE 1

LOCATIONAL PROPERTIES OF SOUTHERN GROUPS IN SAMPLE OBSERVED BY SANDAGE (1975)

Group	l(1950)	b(1950)	$\langle V_0 \rangle$ (km s^{-1})
Antlia	274°	18°	2826
A1060 = Hydra I	270	26	3697
NGC 3557	282	21	2527
NGC 4373	298	23	2996
Centaurus cluster	302	22	3213
NGC 4936	306	32	3074
IC 4296	313	28	3648
IC 4329	318	31	4320

TABLE 2

LOCATIONAL PROPERTIES OF ABELL CLUSTERS IN DISTANCE CLASSES 0, 1, AND 2

Cluster	l(1855)	b(1855)	V_0/100
A194	110	−63	54
A262	104	−25	50
A347	109	−18	58
A400	138	−45	69
A407	118	−20	142
A426	118	−13	55
A539	163	−17	80
A548	198	−24	117
A569	136	+23	58
A576	128	+27	121
A779	158	+45	60
A1060	237	+27	37
A1185	170	+68	105
A1213	168	+70	86
A1228	153	+70	103
A1314	118	+64	100
A1367	202	+74	62
A1656	23	+87	69
A1736	280	+35	129
A2147	356	+44	107
A2151	359	+44	111
A2152	357	+44	112
A2162	16	+45	95
A2197	32	+43	91
A2199	30	+43	94
A2634	71	−33	92
A2666	74	−34	82

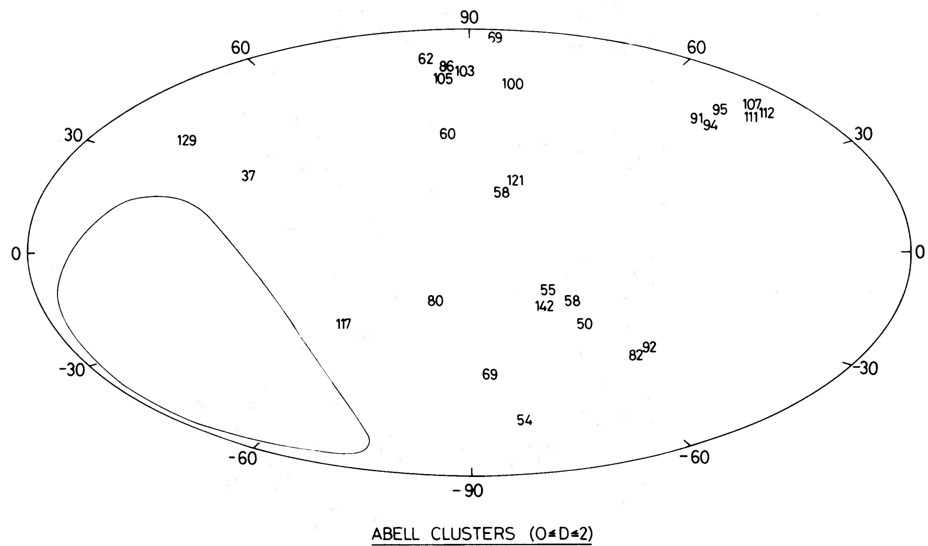

FIG. 4.—Redshift map for the Abell clusters in distance classes 0, 1, and 2. See legend to Fig. 2 for further details. See Table 2 for cluster identifications.

A1367. Figure 6 is a redshift map of the Rubin *et al.* (1976) galaxies in the 6100–8500 km s^{-1} window, which is approximately the range for the galaxies in the Coma supercluster. By comparing Figures 4 and 6, we see that the Coma supercluster is part of a larger structure which includes A779 and appears to extend more than 200 Mpc across the celestial sphere. This structure seems to end abruptly to the right of the Coma cluster, where a vast void exists. Figure 6 also shows the presence of additional Sc I–Sc II galaxies in the redshift range of the Coma supercluster scattered rather irregularly across the sky.

Figure 7 is a redshift map of the Rubin *et al.* (1976) galaxies in the range 4200–6000 km s^{-1}, which is centered near the maximum of the Sc I–Sc II luminosity function and bounds the redshifts of the Perseus supercluster (Tifft and Gregory 1977). It is evident that the Perseus supercluster is part of a structure which may extend irregularly $\sim$200 Mpc across most of the sky. From Figure 7 and from the other redshift maps as well (which are, however, more diluted because of the Rubin *et al.* apparent magnitude selection criterion), one could gain the impression that the universe is an irregular three-dimensional "net"—chains and clumps of galaxies separating vast voids. This model is in general agreement with the one advanced by Joeveer *et al.*

It should be emphasized that the "peaks" in the

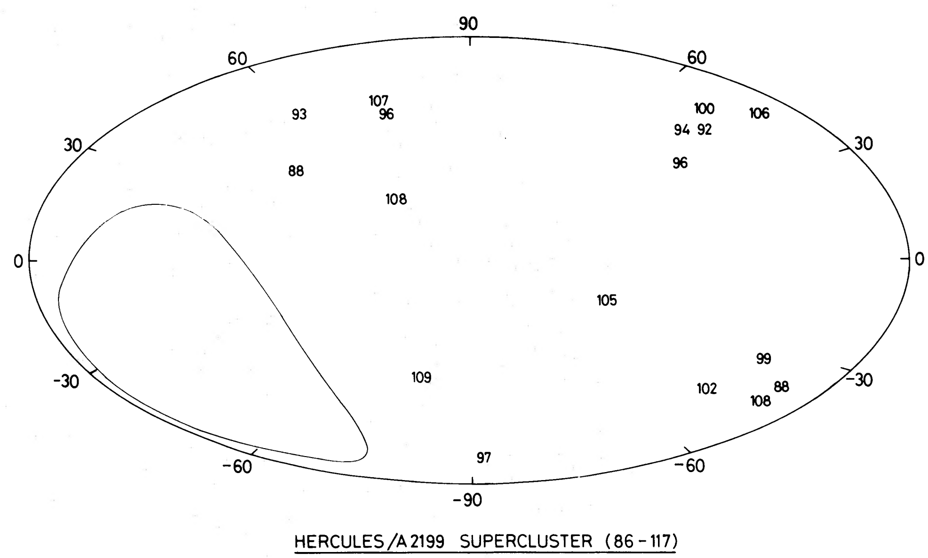

FIG. 5.—Redshift map for the galaxies with 8600 km s^{-1} $\leq V_0 \leq$ 11,700 km s^{-1} in the Rubin *et al.* (1976) sample. See legend to Fig. 2 for further details.

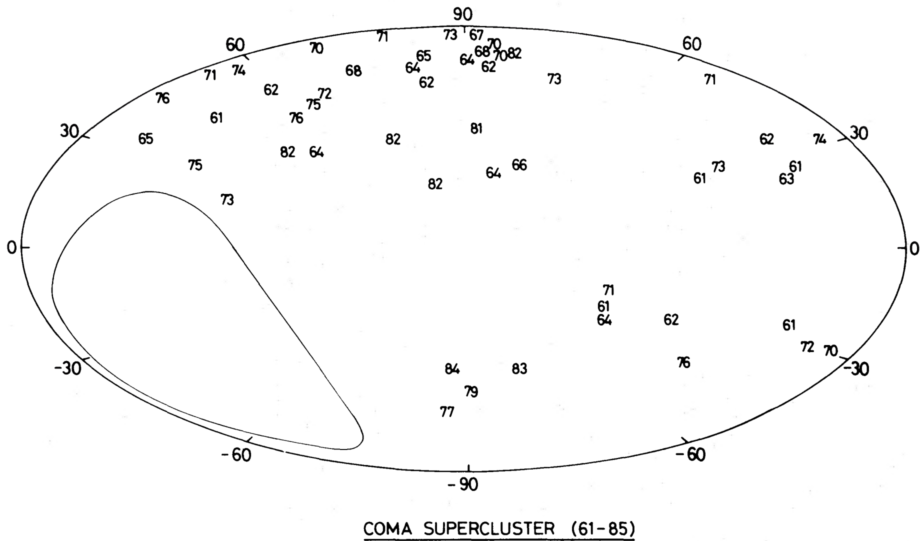

FIG. 6.—Redshift map for the galaxies with 6100 km s^{-1} $\leq V_0 \leq$ 8500 km s^{-1} in the Rubin *et al.* (1976) sample. See legend to Fig. 2 for further details.

redshift histogram (Fig. 1*a*) and the redshift maps (especially Figs. 6 and 7) *do not* imply that the Hydra/Centaurus, Perseus, Coma, and Hercules superclusters are parts of shells of galaxies centered on the observer. The three-dimensional "net" structure persists in the radial direction as well as across the sky. This is evident from examination of polar plots of redshift versus Galactic longitude (Figs. 8 and 9). Shells in space would transform into circular rings in these plots, but such features are not evident.

Rubin, Thonnard, and Ford (1976) find an anisotropy across the sky in the Hubble modulus (log $V_0 - 0.2M_c$) (where M_c is an "appropriately corrected absolute magnitude") of their homogeneous sample of Sc I–Sc II galaxies. They interpret this result to mean that the Local Group is moving with a velocity of 450 $\pm$ 125 km s^{-1} relative to these galaxies. Doroshkevich and Shandarin (1977) suggest that the Rubin *et al.* (1976) galaxies are located primarily in two supercluster pancakes (the Coma and Perseus pancakes [Einasto *et al.* 1978]) moving with different velocities relative to the Local Supercluster. They conclude that the typical peculiar velocities of the pancakes which follow from the theory of galaxy formation based on the nonlinear theory of gravitational instability (Zel'dovich 1970, 1973; Zel'dovich and Novikov 1975)

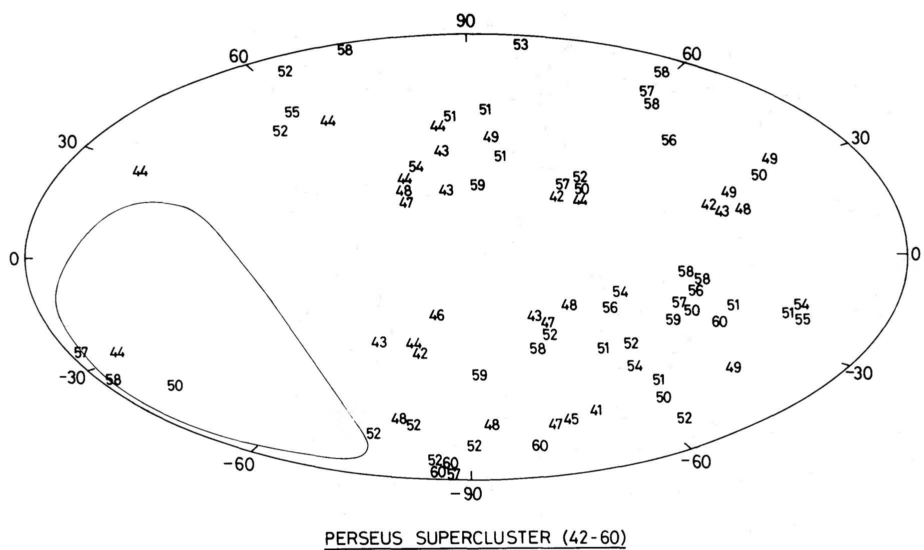

FIG. 7.—Redshift map for the galaxies with 4200 km s^{-1} $\leq V_0 \leq$ 6000 km s^{-1} in the Rubin *et al.* (1976) sample. See legend to Fig. 2 for further details.

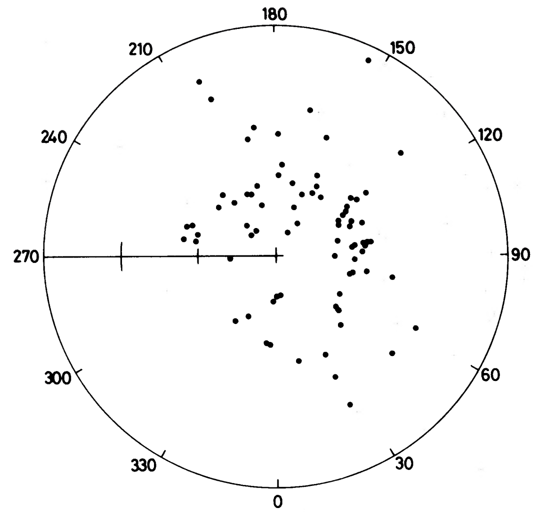

FIG. 8.—Polar plot of redshift (circle radius is 15,000 km s^{-1}) versus Galactic longitude (l) for all galaxies in the Rubin *et al.* (1976) sample with Galactic latitude $b \geq 0°$.

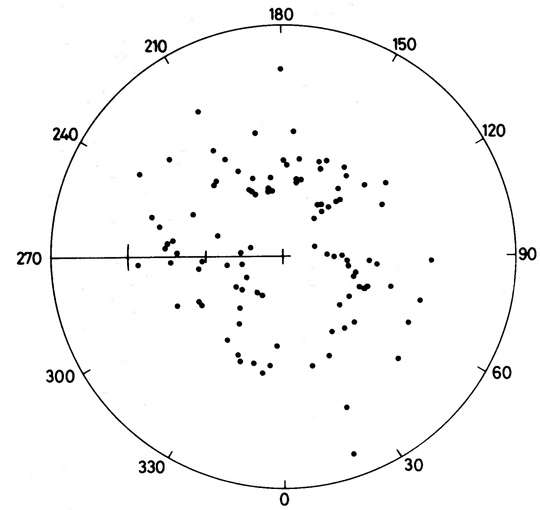

FIG. 9.—Polar plot of redshift (circle radius is 15,000 km s^{-1}) versus Galactic longitude (l) for all galaxies in the Rubin *et al.* (1976) sample with Galactic latitude $b < 0°$.

are in accord with the anisotropy observed by Rubin, Thonnard, and Ford (1976). On the other hand, Sandage and Tammann (1975), Fall and Jones (1976), and Schechter (1977) point out that various uncertainties, including biases resulting from ignoring the inhomogeneous distribution of galaxies in the universe, could lead to a spurious anisotropy. The structures which we have found by examining the Rubin *et al.* (1976) data are consistent with either of these possibilities.

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