LARGE-SCALE STRUCTURE:
THE CENTER FOR ASTROPHYSICS REDSHIFT SURVEY

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ABSTRACT. Two slices of the Center for Astrophysics (CfA) redshift survey extension are now complete. The survey indicates that galaxies are distributed on the thin surfaces of "bubble-like" structures. The voids in the survey have diameters as large as 5,000 km s^{-1}. These structures challenge theories for the formation of large-scale structure in the universe and suggest new approaches to several problems in the field.

1. INTRODUCTION

Each of the large redshift surveys completed during the last ten years has caused significant evolution in our understanding of the nature of the distribution of galaxies. A perusal of the volumes from the the IAU Symposia in Tallinn and Kolymbari clearly demonstrates the continuing change in perspective (Longair and Einasto 1978; Abell and Chincarini 1982). In Tallinn, Joêveer and Einasto (1978) suggested that the large-scale distribution of galaxies has a "cellular" pattern in which rich clusters are connected by "filamentary" structures. The data at that time were incomplete and only adequate to hint at such structure. By 1982, the year of the meeting in Crete, several large redshift surveys were under way and some were complete (Davis, Huchra and Latham 1983; Kirshner *et al.* 1983 (KOSS); Giovanelli 1983). Voids, particularly ones as large as that in Boötes, and filaments like the one in the Pisces-Perseus region were the apparent features of the distribution in redshift space which commanded the attention of both theorists and observers. The ubiquity of such large-scale features was not clear.

Since the meeting in Kolymbari, the number of measured redshifts has more

A. Hewitt et al. (eds.), Observational Cosmology, 301–313.

than doubled. There are now approximately 20,000 galaxies with measured redshifts in the catalog maintained at the CfA (Center for Astrophysics; Huchra *et al.* 1987a). Recently completed surveys continue to modify our picture of the large-scale distribution of galaxies. The deep surveys of Koo, Kron, Munn, and Szalay (1987) indicate that large voids are common at high redshift. The AAT surveys also reveal voids and thin structures perpendicular to the line-of-sight (Peterson *et al.* 1986). The continuing Arecibo survey delineates nearby voids and supports the interpretation of the structure in Pisces-Perseus as a "one-dimensional" filament (Haynes and Giovanelli 1986; Giovanelli *et al.* 1986). In this volume, Dr. Chincarini (1987) reviews these and a host of other observations. The extension of the CfA redshift survey, the subject of this talk, indicates that bright galaxies are distributed on thin sheets — two-dimensional structures — which surround (or nearly surround) vast voids. Large structures appear to be a common feature of all surveys large enough to contain them.

The continually changing picture reflects the attention which has been paid to the design of redshift surveys. Each of the surveys mentioned so far explores a new regime in a sort of "phase space" for observations of large-scale structure. A convenient set of parameters for comparing surveys are effective depth, maximum angular scale covered (solid angle is a less telling measure — the shape of the survey is important), and signal-to-noise (the number of galaxies available to define the structures). Surveys like the KOSS survey (Kirshner *et al.* 1986) of Boötes which consist of widely separated small probes are an efficient way of finding large voids. However, they have low "signal-to-noise" because they they cover only a small fraction of the volume spanned by the probes. Surveys like the CfA survey extension (Huchra *et al.* 1987b) which are complete over a region of large angular scale are less efficient for identifying large voids, but they are necessary for quantitative characterization of the distribution of galaxies over a range of scales.

2. DESCRIPTION OF THE SURVEY

The goal of the CfA redshift survey extension is to measure redshifts for all galaxies in a merge of the Zwicky *et al.* (1961 – 1968) and Nilson (1973) catalogs which have $m_{B(0)} \leq 15.5$ and $|b_{II}| \gtrsim 40°$. There will be $\sim$ 12,000 galaxies in the complete survey; 5,500 redshifts have already been measured. About 1,800 of these galaxies with measured redshifts lie in the "slices" for which the survey is now complete: (1) a slice with $8^h \leq \alpha \leq 17^h$ and $26.5° \leq \delta < 32.5°$ (de Lapparent, Geller, and Huchra 1986) and (2) a slice with $8^h \leq \alpha \leq 17^h$ and $32.5° \leq \delta < 38.5°$. More than 60% of the redshifts were measured with the Mount Hopkins 1.5-meter and the MMT. The mean external error in these measurements is $\sim$ 30 km s^{-1}.

Figure 1 shows the positions of the galaxies from the Zwicky-Nilson merge which have $m_{B(0)} \leq 15.5$, $8^h \leq \alpha \leq 17^h$ and $8.5° \leq \delta \leq 50.5°$. The grid is Cartesian in α

and δ. The deficiency of galaxies west of 9^h and east of 16^h is caused by Galactic obscuration. The bold ticks indicate show the location of the two complete survey strips. The Coma cluster is the dense region at 13^h in the 6° strip.

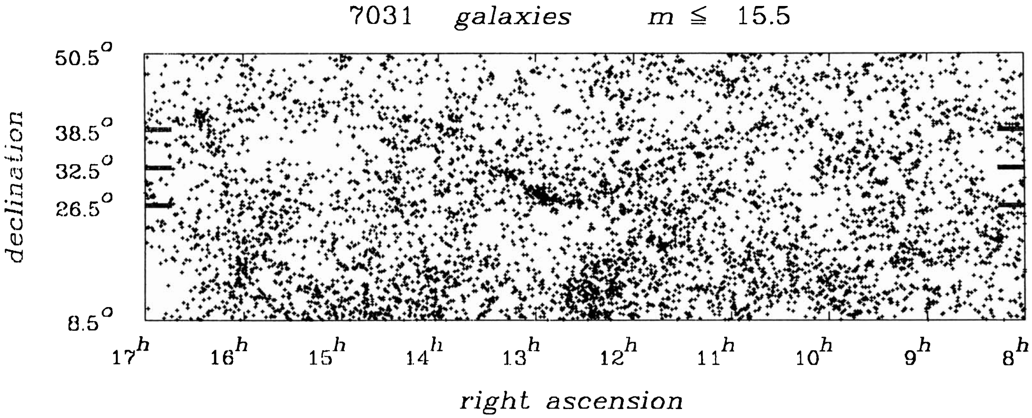


Figure 1. Positions of galaxies in the Zwicky–Nilson merge with $m_{B(0)} \leq 15.5$, $8^h \leq \alpha \leq 17^h$ and $8.5° \leq \delta \leq 50.5°$. The bold ticks indicate the declination limits of the complete redshift survey strips.

3. TOPOLOGY OF THE GALAXY DISTRIBUTION

Observations for the first strip of the survey were completed during the spring of 1986. Figure 2a is a plot of the observed velocity versus right ascension: the strip is 6° thick in declination. The plot includes only the 1067 galaxies with velocities less than 15,000 km s^{-1}. A galaxy with the characteristic luminosity $M^* = -19.4$ ($H_0 = 100$ km s^{-1} Mpc^{-1}; Davis and Huchra 1982) is at 10,000 km s^{-1} in this survey.

In Figure 2a, nearly every galaxy with a velocity less than 10,000 km s^{-1} is in an extended thin structure. The boundaries of the empty regions are remarkably sharp. Several of the empty regions are surrounded by thin structures in which the separation of galaxies is small compared with the extent of the enclosed void. The edges of some of the largest structures may be outside the right ascension limits of the survey. The only pronounced velocity finger in the distribution is the Coma cluster at $\sim 13^h$.

The thin structures in the distribution of galaxies are cuts through two-dimensional sheets; in this slice the structures are *not* one-dimensional filaments. If the

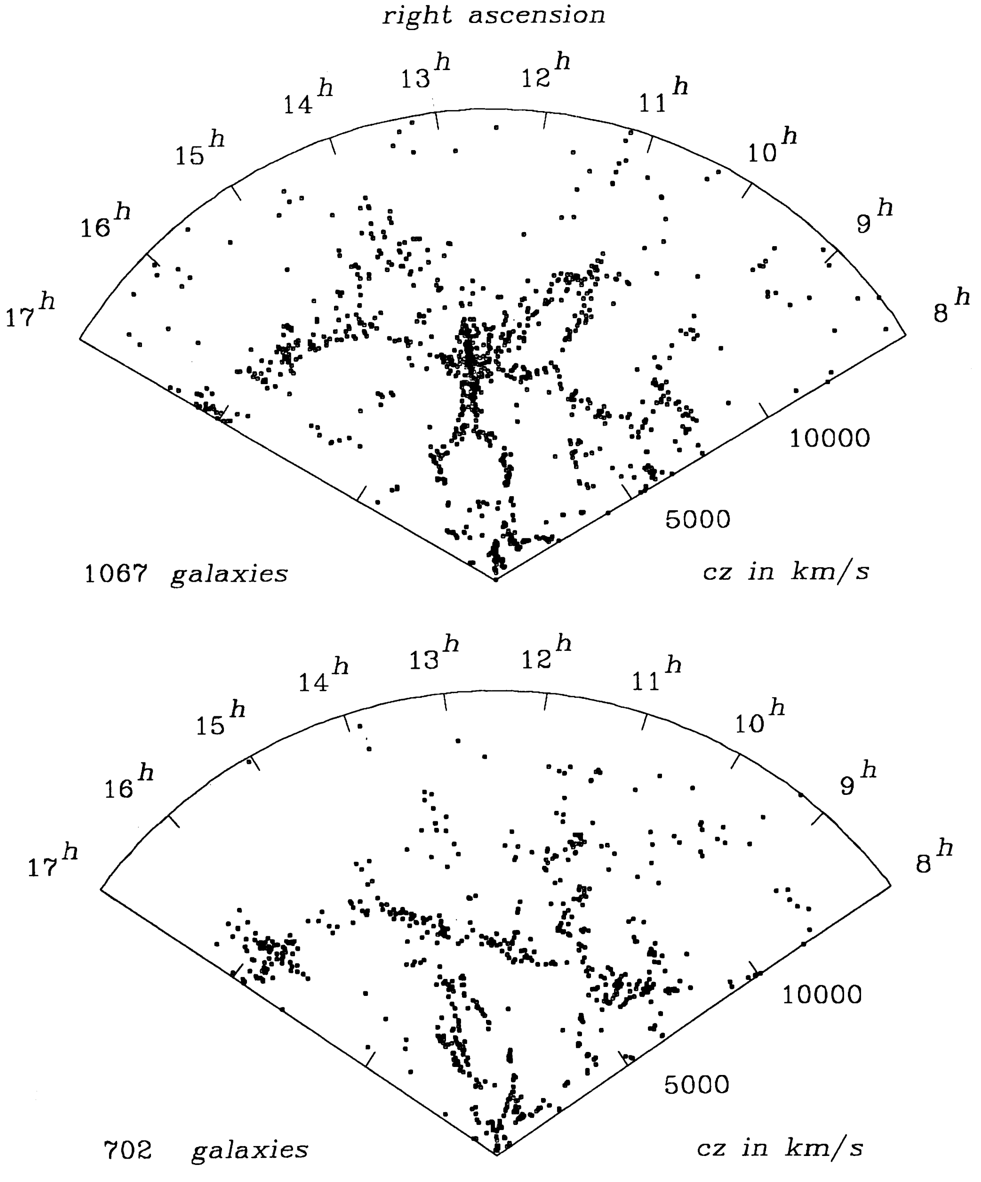
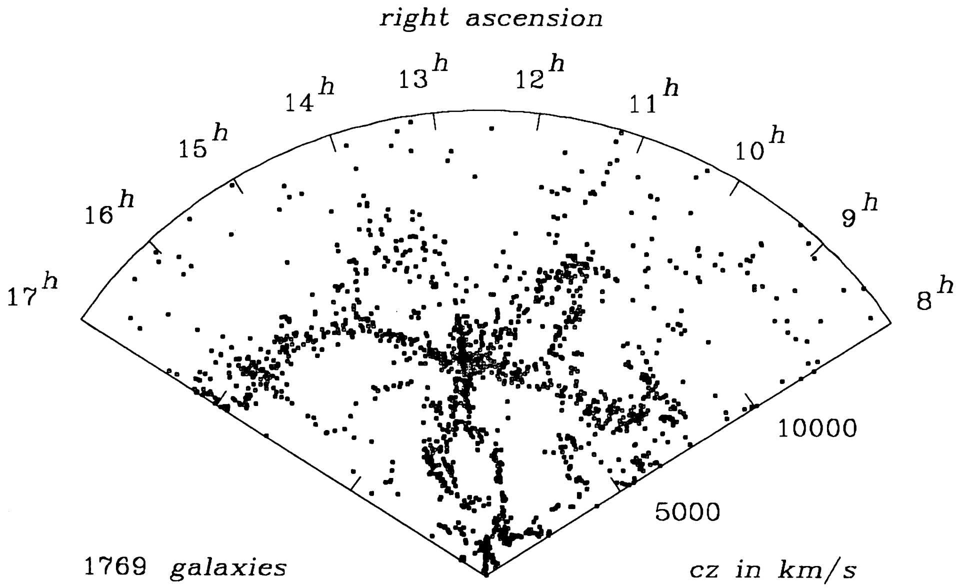


Figure 2a. (top) Observed velocity versus right ascension for the complete survey strip centered at $\delta = 29.5°$. The strip extends for 6° in declination. Only the galaxies with velocities $\leq$ 15,000 km s^{-1} are shown. **Figure 2b.** (bottom) Same as a) but for galaxies in the 6° declination strip centered at 35.5°.



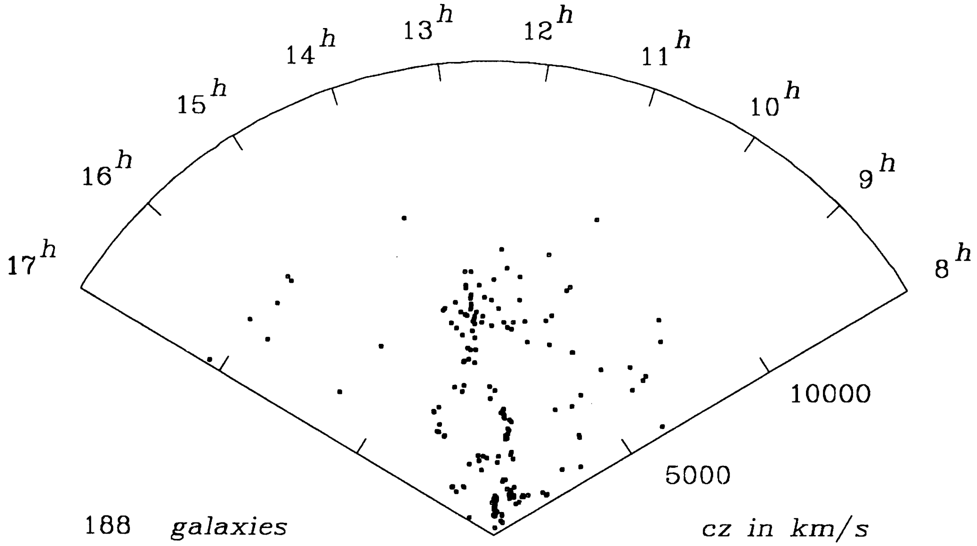


Figure 3. (top) Observed velocity versus right ascension for the two complete strips shown separately in Figures 2a and 2b. **Figure 4.** (bottom) Observed velocity versus right ascension for the survey strip centered at $\delta = 29.5°$ (see Figure 2a) but with a magnitude limit $m_{B(0)} = 14.5$.

$\sim$ 150 Mpc long structure which extends across the entire survey (from 9^h to 16^h between 7,000 km s^{-1} and 10,000 km s^{-1}) is a filament, a thin linear structure should be visible in projection on the sky. There is no such structure in Figure 1 (see de Lapparent, Geller and Huchra 1986). Because structure on the sky can be caused by patchy obscuration and/or by inhomogeneities in the galaxy catalog, structure in the distribution on the sky cannot provide complete proof (or disproof) of the filamentary nature of a structure in redshift space. A second argument against the filamentary nature of the structures in Figure 2a is that several thin, elongated structures lie in the survey slice: the intersection of a thin slice with a three-dimensional network of filaments is *a priori* unlikely to be a two-dimensional network of filaments. Of course, we could have been lucky (or unlucky).

A "bubble-like" structure in which the galaxies lie on thin surfaces surrounding voids accounts for the data. In such a structure, almost all slices will resemble Figure 2a. In this model, the 150 Mpc "filament" is made up of portions of the surfaces of adjacent "bubbles" and clusters like Coma lie in the interstitial regions (where several "bubbles" come together). We observe few, if any, pronounced velocity fingers poking through the shells.

Maps of adjacent slices support this geometric picture of the structure. During the spring of 1987, we completed the survey in the slice centered at $\delta = 35.5°$, just to the north of the strip in Figure 2a. Figure 2b shows the velocity distribution in the second slice. Once again most of the galaxies are in thin structures. Furthermore, these structures are a natural extension of the structures in Figure 2a; the structures are highly correlated in the two slices. The two closed structures at $\sim 11^h$ (9,000 km $s^{-1} \lesssim v \lesssim$ 11,000 km s^{-1}) and at 14^h (7,000 km $s^{-1} \lesssim v \lesssim$ 11,000 km s^{-1}) in Figure 2a are not clearly delineated in Figure 2b. Sampling of these structures may be affected by variations in the magnitude limit of the catalog.

Figure 3 shows the velocity distribution for the two complete strips taken together. The distribution remains remarkably inhomogeneous with empty voids outlined by thin structures. Because the surfaces are curved or inclined, the structures are thicker here than in Figures 2a and 2b. The curvature or inclination is most noticeable for the small void which is centered at 13^h20^m and $\sim$ 3,500 km s^{-1} (in front of the Coma cluster). The diameter of this structure is $\sim$ 2,000 km s^{-1}. The largest low density region in the survey is located between 13^h20^m and 17^h with $4{,}000 \lesssim v \lesssim 9{,}000$ km s^{-1}. The diameter is $\sim$ 5,000 km s^{-1} (50 Mpc in the absence of large-scale flows). The underdensity in this region ($\lesssim 20\%$ of the mean) is comparable with the recent estimates for the void in Boötes. The galaxies inside the structure which are at similar velocities in Figures 2a and 2b may form a tenuous structure.

It is instructive to compare these new surveys with the information available from the CfA survey (Davis *et al.* 1982; Huchra *et al.* 1983) to a limiting magnitude

$m_{B(0)} = 14.5$. Figure 4 shows the slice centered at 29.5° to this limit. Here an M^* galaxy has a velocity of $\sim$ 6000 km s^{-1}. Because the "effective depth" of the earlier survey is comparable with the size of the largest structures in Figures 2a – 3, these structures could not be detected.

The nearby small void centered at $13^h\ 20^m$ and 3500 km s^{-1} can be seen in both Figures 2a and 4. The fainter galaxies in Figure 2a populate the same thin structure which is just barely detectable in Figure 4. Note that the fainter galaxies fill in gaps along the perimeter of the voids. This comparison and other deep probes through the 29.5° slice (Postman, Huchra and Geller 1986) indicate that the distribution of galaxies is independent of absolute luminosity for $M_{B(0)} \lesssim -17.4$. The change in the fractional coverage of the perimeter of the void as a function of luminosity is a problem for attempts to distinguish between "sponge-like" (Gott 1987; Gott, Melott, and Dickinson 1986; Hamilton, Gott, and Weinberg 1987) and "bubble-like" structures. Because the fractional coverage of the surface area of any particular void is poorly defined, it is difficult to identify the borderline between the two topologies.

The 21-cm data (Haynes and Giovanelli 1986) also reveal sheet-like structures in the Perseus-Pisces region. The effective "signal-to-noise" of the data is somewhat lower for these surveys — only about 50% of the galaxies in a sample limited to $m_{B(0)} \lesssim 15.5$ are readily detectable at 21-cm. The smaller area AAT surveys (Peterson *et al.* 1986) provide further evidence of similar stuctures.

4. IMPLICATIONS

One of the important implications of the survey is obvious from inspection of Figure 3: the inhomogeneities in the distribution of galaxies are large compared even with the two slices taken together, a sample comparable in volume with the whole CfA survey to $m_{B(0)} = 14.5$. The new data are a clear demonstration that these samples are not large enough to be "fair". Figure 5 provides a more quantitative demonstration of the significance of the large-scale departures from homogeneity in the sample. The velocity histogram for the two slices differs markedly from the distribution (solid curve) predicted with luminosity function parameters from the $m_{B(0)} \leq 14.5$ sample ($\phi^* = 0.014$ Mpc^{-3}, $M^* = -19.4$, $\alpha = -1.3$). The departures are dominated by the large nearby voids and by the structures which run across the survey between 7,000 and 10,000 km s^{-1}, not by the core of the Coma cluster which contributes only $\sim$ 100 galaxies to the histogram.

It is sobering that the largest structures we observe in the CfA survey extension are the largest we can detect within the constraints placed by the depth of the survey. The size of the inhomogeneities relative to the volume of surveys may underlie unexplained variations in traditional statistics of the galaxy distribution like the luminosity function (Schechter 1976; KOSS 1983; Bean *et al.* 1983; Davis and Huchra 1982) and the two-point correlation function at large scale (cf. Groth and Peebles 1977; Davis and Peebles 1983; Kirshner, Oemler, and Schechter 1979; Shanks *et al.* 1983). When the inhomogeneities are large compared with the sample volume, mean quantities are not well-defined.

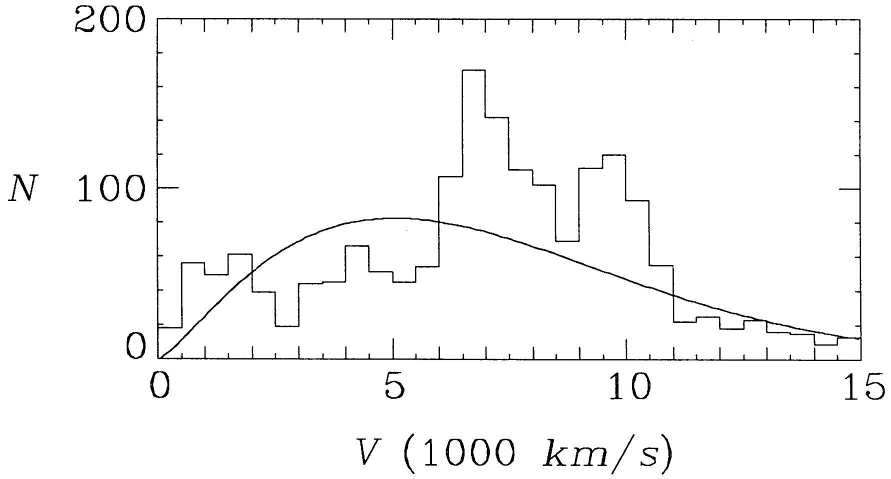


Figure 5. The velocity distribution for the entire complete sample displayed in Figure 3. The smooth curve is the distibution expected for a uniform galaxy distribution with the luminosity function parameters derived from the CfA survey to $m_{B(0)} = 14.5$.

In the absence of a "fair" sample, there are some statistical measures of the properties of individual structures which may be useful for comparing the data with simulations (see de Lapparent 1986; de Lapparent, Geller, and Huchra 1987). Both the voids and the surfaces may be characterized quantitatively. The frequent mention of the "size" of the void in Boötes is a demonstration of the power of a measure of the scale of the largest observed structures. The distribution of sizes of voids is an important test of models (the theoretical situation is reviewed by Dr. Dekel (1987) in this volume); the small-scale end is a constraint on hot dark matter models (Zel'dovich 1970; Doroshkevich *et al.* 1980; Centrella and Melott 1983) and the large-scale end is the most demanding for cold dark matter models (Davis *et al.* 1985) and for the explosive models (Ostriker and Cowie 1981; Ikeuchi 1981; Saarinen, Dekel, and Carr 1986). Determination of the distribution of sizes of voids requires samples much larger than those currently available.

If rich clusters lie in interstices between large voids, the cluster correlation function (Hauser and Peebles 1973; Bahcall and Soneira 1983; Postman, Geller, and Huchra 1986) reflects the spectrum of voids. The puzzling contrast between individual galaxies and clusters of galaxies as tracers of the large-scale matter distribution (cf. Kaiser 1984) will probably only be clearly resolved when galaxy and cluster redshift surveys overlap sufficiently.

Another interesting and possibly measurable characteristic of the voids is the elongation along the line-of-sight. If the density inside is low compared with the average surroundings, the voids should be expanding relative to the average cosmological flow and the structures should appear alongated in redshift space. The magnitude of the flow depends upon the details of the underlying physics for the formation of the structures (Peebles 1982; Hoffman, Salpeter, and Wasserman 1983; Bertschinger 1985). In a large enough sample containing many voids the intrinsic spatial geometry of the voids will average out and any net elongation along the line-of-sight may be interpreted as the result of residual expansion. The measurement of distances to galaxies in the structures offers a more direct probe for large-scale flows associated with the existence of voids. Many spiral galaxies lie in the extended sheets offering the possibility of using the infra-red Tully-Fisher technique (Aaronson, Huchra, and Mould 1979) to obtain limits at the few hundred kilometer per second level over scales of fifty megaparsecs.

The thinness ($\lesssim 500$ km s^{-1}) and coherence of the surfaces provide other constraints. The thickness as a function of orientation with respect to the line-of-sight may constrain the internal velocity dispersion and the spatial thickness. The "uniformity" of the surfaces may provide a constraint on Ω (see Peebles 1986). If $\Omega =$ 1 and the distribution of galaxies marks the distribution of matter, it is unlikely that a smooth shell can persist over a Hubble time; gravity should cause the matter to clump up and "fingers" poking through the "shells" should be a more common feature in redshift space. If the actual density contrast in shells is small and the voids are filled with a nearly uniformly distributed dark matter (with Ω close to 1), the structures could still be in the linear regime. If, on the other hand, Ω is low (say $\lesssim 0.2$ as indicated by dynamical analyses of groups and clusters), the structure could set in early on and then just stretch with the universal expansion.

The study of the dynamics of individual rich clusters is a final example of a problem where the new survey data suggest a revised approach. The Coma cluster is an illustration of the difficulty. In Figure 2a the edge of the largest shell is projected nearly along the line-of-sight adjacent to the velocity finger of Coma. The structures are separated somewhat in declination, but they are sufficiently closely associated that the determination of the velocity dispersion of the cluster could be compromised by the spatial extent of the shell. Contributions from these shells would generally bias the velocity dispersions upward. The relationship between the topology of large-scale structure and the properties of individual clusters is also important for exploration of the infall pattern at large distances from the cluster center (see, for example Shectman 1982). It is not yet clear to what extent the gravitational field of a cluster drives the surrounding structure.

5. THE FUTURE

During the next year detailed quantitative comparison of the new data with simulations will further refine our understanding of the nature and origin of large-scale structure. The development of statistical measures to characterize the large-scale features in the data is an important first step in this process.

It is well to keep in mind that the maps of Figures 2–3 are maps in redshift space. Distance estimates for the galaxies in these structures are crucial to see how well the distribution in redshift space reflects the structure in three-dimensional position space. We have begun a program to study one of the largest structures. These measurements may indicate how the stuctures we observe fit together with the large-scale flows discussed by Dr. Davies (1987) at this symposium.

The discussion of Section 4 indicates several of the drivers for more extensive redshift surveys. In addition to completion of the CfA survey extension to the limiting $m_{B(0)} = 15.5$, we have begun (in collaboration with J. Thorstensen and G. Wegner at Dartmouth) to survey a $1^\circ \times 100^\circ$ strip to a limit of $m_{B(0)} = 17.5$. Both of these surveys should be complete within the next five years — perhaps they will bring further surprises as we sample more of the available "phase space."

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DISCUSSION

FANG: Since the relationship between the richness of clusters and the sizes of clusters or voids is important in fractal theory, is such a relationship found in your survey?

GELLER: We speculate that there is such a relationship, but we are far from having enough data to measure it!

ROWAN-ROBINSON: Do you have types for these galaxies so that you could remove the ellipticals, and hence the cluster 'fingers', and then see the bubbles uncontaminated by 'fingers'?

GELLER: We do not yet have types for all the galaxies in the survey, but we will in the near future.

DEKEL: (1) Isn't the Perseus-Pisces supercluster a filament?

(2) You've mentioned the 'finger of god' effect that generates elongated structures along the line of sight from velocity dispersion. Infall velocities generate thin walls perpendicular to the line-of-sight so one should be careful not to over-interpret the result in terms of "thin bubbles".

GELLER: (1) Before being absolutely convinced that the Perseus-Pisces supercluster is a filament I would like to see a careful analysis of the effects of observation in the region.

(2) What you say is true, but I think it is difficult to produce such thin, extended structures on the observed scales. The case will become clearer when we have better quantitative characterization of both the data and the models. The "bubble-like" geometry does not rule out your suggestion.

SZALAY: Peebles' argument for the homogeneity of the universe is based upon the excellent scaling of the angular correlations with depth. How can one reconcile this with the appearance of larger and larger structures as the redshift catalogues reach deeper?

GELLER: It's difficult! The only clue I see is that the correlation function is measured on scales small compared with the structures.