

AN HISTORICAL VIEW: THE DISCOVERY OF VOIDS IN THE GALAXY DISTRIBUTION

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ABSTRACT

voids in the large scale distribution of galaxies were first recognized and discussed as an astrophysical phenomenon in two papers published in 1978. We published the first (Gregory and Thompson 1978) and Joeveer, Einasto and Tago (1978) published the second. The discovery of voids altered the accepted view of the large scale structure of the universe. In the old picture, the universe was filled with field galaxies, and occasional density enhancements could be found at the locations of rich galaxy clusters or superclusters. In the new picture, voids are interspersed between complex filamentary supercluster structure that forms the so-called cosmic web. The key observational prerequisite for the discovery of voids was a wide-angle redshift survey displayed as a cone diagram that extended far enough in distance to show a fair sample of the universe (i.e. well beyond the Local Supercluster). The initial impact of the 1978 discovery of voids was stunted for several years by theoretical cosmologists in the West who were not quite sure how filaments and voids could emerge from what otherwise appeared to be a homogeneous universe. After it became clear several years later that theoretical models of structure formation could explain the phenomenon, the new void and supercluster paradigm became widely accepted.

Subject headings: history and philosophy of astronomy — large scale structure of universe

1. INTRODUCTION

In the mid-1970's two independent research programs revealed the beautiful void and supercluster structure of the universe, what is now referred to as the cosmic web. We initiated the first of these research programs (Gregory and Thompson 1978). The second was an entirely separate effort by observational astronomers in Estonia and theoreticians in Russia (Joeveer, Einasto and Tago 1978). These two programs could not have been more different, but they both led to the conclusion that there are large volumes in the local universe with diameters $\sim 20 h^{-1}$ Mpc that contain no galaxies whatsoever¹. We called these empty regions "voids" while Joeveer et al. at first simply called them "big holes".

Our work was empirically driven. The existence of supercluster structure was widely known in this era, and Abell (1961) had called attention to "second order clusters", i.e. congregations of rich cluster cores. Our aim was to understand the galaxy distribution in and around these collections of Abell clusters. For example, we asked whether adjacent Abell cluster cores are isolated density enhancements or whether they are interconnected by "bridges" of galaxies. Because the nearest rich Abell clusters are distributed within a volume that extends to distances of $\sim 100 h^{-1}$ Mpc, we designed our redshift surveys to sample the appropriate volume. Our first target was the Coma and A1367 cluster pair, and it was in the large foreground volume between the Milky Way and the Coma/A1367 supercluster that we identified the first

voids. Our work was not related to nor driven by any theoretical model of structure formation.

The Estonian work was aimed at testing a specific model of structure formation championed in the 1970's by the prominent Russian cosmologist Yakov Zel'dovich. Zel'dovich (1970) postulated the so-called top-down model of galaxy formation. In his model, large supercluster-sized structures are the first to form, and individual galaxies fragment out of the larger collapsing structures. These models have not stood the test of time, but in the mid-1970's Joeveer, Einasto and Tago (1978) collaborated with Zel'dovich and mapped the galaxy and cluster distribution (using catalogues containing known galaxy redshifts) over volumes similar to those we were studying. Further historical details about this research program can be found in Einasto (2009).

In the 1970's the hierarchical clustering model (so-called bottom-up model) was most popular in the West, but in its original form it could not explain, ab initio, the existence of voids as large as those reported in Gregory and Thompson (1978). At first, those who held fast to the early hierarchical model acknowledged that the observed "holes" exist in the galaxy distribution, but they postulated that they appeared naturally as a result of random statistical processes. When we presented our evidence for voids as discrete astrophysical entities with borders defined by filamentary structures, we encountered skepticism that is documented most clearly in Soneira and Peebles (1978) where they said the following: "We know that the eye does tend to judge in a biased way—for example, one readily picks out "chains" of points in a uniform random distribution". In other

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¹ h = Hubble constant/100 km s⁻¹ Mpc⁻¹

words, the filamentary structures that we identified as the walls of voids were, according to their interpretation, nothing more than false visual constructs. Not everyone held this extreme view, of course, but the immediate impact of the early redshift survey work was diminished despite the fact that the voids that we identified in the Coma/A1367 foreground (and their filamentary walls) have stood the test of time and are just as dramatic today as they were when we first saw them in the mid-1970's.

Fortunately, in this same era advances were being made in computer simulations aimed at modeling the growth and evolution of structure in the large scale distribution of galaxies. These models generally used as a starting point a simple galaxy distribution but eventually included dark matter (either hot or cold). Even these early evolutionary models showed how dramatic filamentary structure can develop in the galaxy distribution over time, and by doing so, they removed the theoretical prejudice against the existence of voids. At first the numerical simulations were relatively simple (Aarseth et al. 1979 and Doroskevich et al. 1980), but the level of sophistication rapidly increased so that by 1983 it was possible for the first time to begin realistically testing key features of the large scale galaxy distribution (Melott 1983, Frenk et al. 1983, to mention just two).

This brief summary provides a context for understanding how the discoveries that emerged from the early galaxy redshift surveys influenced theoretical models of structure formation. Our aim in what follows is to document the redshift surveys published in the first decade after this research began.

2. EARLY REDSHIFT SURVEYS

The redshift survey revolution of the 1970's began when high-voltage image intensifier devices came into wide use and displaced the photographic plate as the primary detector in astronomical spectroscopy. To measure a redshift accurate to ± 100 km/s, a photographic exposure of ~ 2.5 hours had previously been required for an $m \sim 15$ galaxy. An image intensifier system could produce a similar result in 10 to 15 minutes. Significant numbers of new redshifts began to be published soon after the Kitt Peak National Observatory 2.1-m telescope and the Steward Observatory 2.3-m telescope were both equipped with image tube spectrographs. It is at this point that the Redshift Survey Timeline begins (Table 1).

Key participants in the early work included the late Herb Rood as well as Guido Chincarini, William Tift, Stephen Gregory, Laird Thompson, and Massimo Tarenghi. Gregory and Thompson had been graduate students of Tift at the University of Arizona. Tarenghi was Tift's postdoctoral researcher. Herb Rood (then at Michigan State University) and Guido Chincarini (then at the University of Oklahoma) formed a separate team.

The earliest redshift surveys have been called pencil beams because target galaxies were selected from cluster cores that span a small solid angle. Table 1 contains a complete list of the galaxy redshift surveys (including the pencil beam surveys) published in the period 1971-1981. Hints of the large scale structure first began to appear as irregularities in the redshift distribution in the pencil beam foregrounds. But to see such structure with clarity, a redshift survey had to probe to $m \sim 15$. Sur-

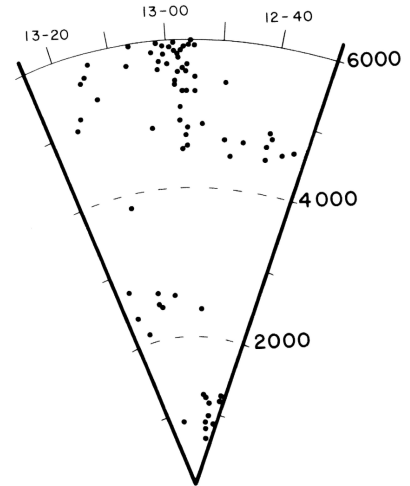


FIG. 1.— Tift and Gregory (1976) presented this diagram to display their redshift survey for the Coma cluster to $r=6^\circ$. This was the first use of a cone diagram in the *Astrophysical Journal*.

veys to $m \sim 14$ showed no significant structure because their distance range was inadequate, and they could not sample foreground structure in any detail. With perfect hindsight, any observer who pushed to $m \sim 15$ in a pencil beam survey might have said that they saw initial hints of the structure, but no one immediately grasped its meaning.

A complete description of the large scale structure required formulating a new three-dimensional picture of the galaxy distribution, one that includes voids interspersed between supercluster structure. The concept of a galaxy supercluster was well developed by the 1970's (c.f., Oort 1983), and yet those who accepted the existence of superclusters assumed that they were simple density enhancements embedded in a uniform field of background galaxies. Others suggested that superclusters had a core-halo structure with a halo that slowly merged into the uniformly distributed field population of galaxies. So it was the discovery of voids – and not superclusters – that provided the basis for the paradigm change.

The primary catalyst for this discovery was the cone diagram: a polar plot with redshift used for the radial coordinate and a galaxy's angular position on the sky used as the azimuth (the third dimension being projected into the plane of the plot). Of course, all modern redshift surveys like CfA, SDSS, 2dF, etc. rely on this diagram to display their data. Those who used the cone diagram for the first time (Tift and Gregory 1976; Gregory and Thompson 1978; Joeveer, Einasto and Tago 1978) were the first to visualize the void and supercluster structure. Table I lists how all authors plotted their redshift data.

In Chincarini and Rood's first redshift survey paper, they completed a pencil beam survey for the Perseus cluster and then determined its virial mass. Their second and third papers list data from the KPNO 2.1-m telescope, and then for three years they published no redshifts. In the mean time Tift began his work at the Steward Observatory 2.3-m telescope. When Chincarini and Rood resumed their work with a study of the Coma cluster, Tift and graduate student Gregory were doing same. Tift and Gregory worked in the central regions of Coma

(to $r = 6^\circ$) while Chincarini and Rood aimed to trace the Coma cluster to a radial distance of 14° by surveying primarily to the west of the cluster core. Both groups aimed to collect complete samples to $m = 15$, and they began the transition away from the narrow pencil beam surveys.

Fig. 1 shows the Tift and Gregory (1976) Coma cone diagram. This is the first redshift survey shown as a cone diagram. In their discussion Tift and Gregory (1976) note the lack of field galaxies, and in the caption to their cone diagram, they say that the foreground is “devoid” of galaxies. The Tift and Gregory survey of Coma covered too narrow an angular span to include a complete void (from one wall through the empty region and on to the other wall). An average void spans $20 h^{-1}$ Mpc and at the most distant extent they surveyed $12.6 h^{-1}$ Mpc.

Chincarini and Rood published papers in 1975 and 1976 (just before and just after Tift and Gregory 1976), but they always plotted their redshifts as a function of radial distance from the core of Coma, and their plots were square. By making a radial analysis, they essentially destroyed 3D information. In fact, Chincarini and Rood never discussed 3D structure in any of the papers they published prior to 1978. They talked about “redshift segregation” whenever their survey intercepted first a void and then a supercluster filament in the foreground, but they never gave a physical interpretation as to what it meant, i.e. they never mentioned concepts like “holes” or “voids”. Rood and Chincarini discussed their views of the large scale galaxy distribution most clearly at the end of their last observational paper on the Coma cluster (Chincarini and Rood 1976a). They used the following words: “The large sizes of clusters and their fading into low-density supercluster backgrounds leave little if any space between them. On the other hand, Figure 3 clearly shows also a pronounced effect of segregation of redshifts.”

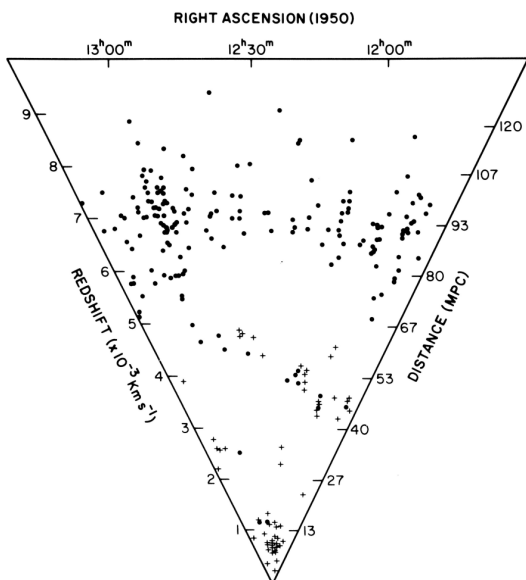


FIG. 2.— The Coma/A1367 supercluster region from Gregory and Thompson (1978). The core of Coma is the elongated feature on the far left and A1367 the weaker elongated feature on the far right. A bridge of galaxies connects the cluster cores, and in the foreground are the first recognized voids.

In May, 1975, we submitted an observing proposal to Kitt Peak National Observatory to use the 2.1-m telescope for a new redshift survey. In our proposal, we posed the hypothesis that the two rich Abell clusters Coma and A1367 are enveloped in a common supercluster. Since they are separated by 21° in the plane of the sky, our aim was to survey a slice in the intercluster region between Coma and A1367 with dimensions 4° wide and 19° long to a depth of $m = 15.0$. We predicted that we would detect an over-density of galaxies (a bridge at their common redshift) in the region between the two clusters. This proposal was accepted, and we collected the new redshifts in April, 1976.

The redshifts in our Coma/A1367 survey were measured and plotted in a cone diagram by the early summer, 1976 (reproduced here as Fig. 2). This plot displays the entire galaxy sample in the region that surrounds and includes Coma and A1367 ($11^\circ \times 23^\circ$) and not the smaller area ($4^\circ \times 19^\circ$) mentioned in our observing proposal. Fig. 2 is the first wide-angle cone diagram that displays a complete magnitude-limited sample to $m = 15.0$. It is not a pencil beam survey: at the deepest extent it spans $36 h^{-1}$ Mpc across the sky. Upon seeing this plot we immediately realized the significance of the irregular distribution of galaxies that had appeared in the foregrounds of the early pencil beam surveys.

Our Coma/A1367 paper (Gregory and Thompson 1978) arrived at the *Astrophysical Journal* on September 7, 1977. It discusses for the first time the large scale structure using the new paradigm. We list here the key points that are unique to this paper.

- We recognized huge empty regions in the 3D plot of our survey volume and for the first time used the word “void” to describe them.
- We outlined possible hypotheses that might explain the void phenomenon by using the following words: “It is an important challenge for any cosmological model to explain the origin of these vast, apparently empty regions of space. There are two possibilities: (1) the regions are truly empty, or (2) the mass in these regions is in some form other than bright galaxies. In the first case, severe constraints will be placed on theories of galaxy formation because it requires a careful (and perhaps impossible) choice of both Ω (the present mass density/closure density) and the spectrum of initial irregularities in order to grow such large density irregularities...” It seemed impossible to us at the time because cold dark matter had not yet been proposed.
- The abstract to our paper states: “there are large regions of space with radii $r > 20h^{-1}$ Mpc where there appear to be no galaxies whatever.”
- Before the observations were made, we had hypothesized the existence of a bridge of galaxies between Coma and A1367. Our 3D cone diagram confirmed it. Today this bridge of galaxies is a small segment of what is often called “The Great Wall”.
- The general structure shown in our cone diagram includes the body, the right leg and right arm of what some call the “Coma stickman”.

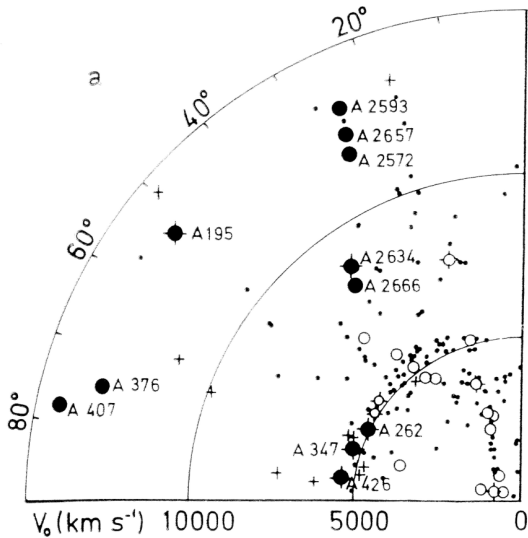


FIG. 3.— Redshift cone diagram of the south galactic hemisphere by Joeveer, Einasto, and Tago (1978). Large filled circles represent clusters of galaxies. Small filled circles represent galaxies. They note the existence of “large holes” in the 3D distribution.

The sharp contrast between the description of the large scale distribution of galaxies as given by Gregory and Thompson (1978) and that of Chincarini and Rood (1976a) explains why a paradigm change occurred.

Table 1 includes only papers that appeared in refereed journals and omits papers that were not refereed: observational publications, presentations made at meetings like the American Astronomical Society, and at conferences like the Tallin conference (IAU Symposium No. 79) held in Tallin, Estonian SSR, September 12-16, 1977². The papers presented at this conference were published in “The Large Scale Structure of the Universe” (Longair and Einasto 1978). This conference was an important event in the early study of the large scale distribution of galaxies. Milikel Joeveer and Jaan Einasto discussed preliminary results that they later published in a refereed journal as Joeveer, Einasto, and Tago (1978). Our Coma/A1367 supercluster manuscript arrived at the *Astrophysical Journal* five days before the conference began, and we had no prior knowledge of any presentations that would be made at IAU Symposium No. 79 except for one by Tift and Gregory that briefly mentions Gregory and Thompson (1978).

The Joeveer, Einasto and Tago (1978) paper is an interesting study of the 3D distribution of both galaxies and clusters of galaxies in the south galactic hemisphere. They present several cone diagrams that display the large scale structure in a region of sky $70^\circ \times 70^\circ$. Their cone diagrams show large empty regions, regions that they call “big holes”. Because their galaxy redshift data were taken from previously published sources (the major source being the Second Reference Catalogue of Bright Galaxies by de Vaucouleurs et al. 1976), Joeveer et al. (1978) do not claim to present a complete magnitude-limited survey. Our surveys always aimed to be magnitude-limited because critics in the 1970’s were quick to raise the possibility that empty regions appeared

² Neither Gregory nor Thompson attended the Tallin conference. Gregory submitted a request to attend, but his request was denied.

empty due to incomplete sampling. The Joeveer et al. (1978) paper was published in the November issue of *Monthly Notices of the Royal Astronomical Society*, five months after our paper on Coma/A1367. Their paper contains four cone diagrams (four different cuts through the same survey area) as well as a reference to Gregory and Thompson (1978). Figure 3 below displays one of these four cuts.

We continued our program to study the galaxy distribution in and around the nearest Abell clusters. In Gregory, Thompson and Tift (1981), we investigated the properties of the long filamentary chain of rich clusters in Perseus, and in Gregory and Thompson (1984) we studied another double cluster, A2197 and A2199. A larger collection of the early redshift survey workers analyzed the properties of the Hercules supercluster region (Tarenghi et al. 1979), and in Chincarini, Thompson and Rood (1981) an extended filament or bridge of galaxies was found to stretch $44h^{-1}$ Mpc from the A2197/A2199 supercluster to the Hercules supercluster. This publication is significant because it demonstrates the filamentary nature of the large scale structure over an extensive length scale. In this case, the filament extends primarily in depth rather than in an angular span across the sky. We note that none of these studies from the early 1980’s are so-called pencil beam surveys. The survey areas were large enough to include multiple Abell cluster cores and revealed other voids and supercluster structure.

It is a common misconception that the early phases of the Center for Astrophysics (CfA) redshift survey contributed to the paradigm change. In Table 1 it is easy to see how the CfA work progressed relative to the work of the Arizona groups. The first CfA study by Davis, Geller and Huchra (1978) had a limiting magnitude of $m = 13.0$. It was shallow and showed no evidence of any structure. Their stated aim in undertaking this first survey was to measure the mean mass density of the universe. The second CfA milestone paper was by Davis, Huchra, Latham and Tonry (1982). With a survey limit at $m = 14.5$, it shows hints of the large scale structure. But by the time this paper was published in 1982, the nature of voids and supercluster structure was widely known and widely discussed. For example, Zeldovich, Einasto and Shandarin (1982) published a review article for *Nature* entitled “Giant Voids in the Universe”. In addition to technical references cited in Table 1, popular accounts were also being published (Chincarini and Rood 1980; Gregory and Thompson 1982). The later article for *Scientific American* is entitled “Superclusters and Voids in the Distribution of Galaxies”.

3. THE SECOND WAVE REDSHIFT SURVEY WORK

Other research groups began to substantiate the new void and supercluster structural features in the galaxy distribution. The field grew so rapidly in the mid-1980s – a time when CCD cameras began to replace image intensifiers – that it is virtually impossible to make the last half of Table 1 complete. One important group that contributed to the second-wave included Robert Kirshner, Augustus Oemler, Jr., Paul Schechter, and Stephen Shetman. During the late 1970’s they measured galaxy redshifts in three small survey fields, each separated by 35° on the sky (in the direction of the constellations Bootes and Corona Borealis) with the aim of determin-

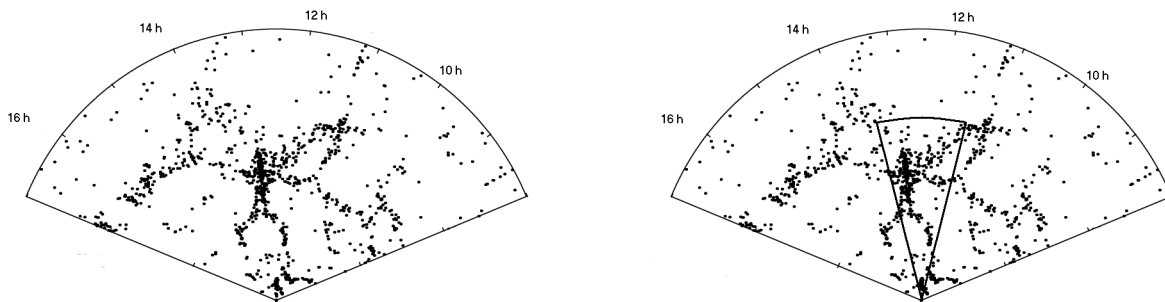


FIG. 4.— Left: The original redshift data from de Lapparent et al. (1986) is shown in this plot with redshift increasing from zero at the lower apex to 15,000 km/s along the arc of right ascension. Right: The Gregory and Thompson (1978) redshift survey area is superimposed on a re-plot of the de Lapparent et al. (1986) data. Because the core of A1367 is at Dec. = 21° , it is not included in this slice, and its Finger of God feature is not present.

ing the galaxy luminosity function. After learning about voids from the early redshift survey papers, they noticed a deficiency of galaxies in the redshift interval between 12,000 km/s and 18,000 km/s in all three of their narrow survey fields. On this basis they speculated that the entire region between their three small survey fields could be “A million cubic megaparsec void” (Kirshner 1981). In the end (Kirshner et al. 1987), the volume of the Bootes void was remeasured to be 1/3 the value quoted in the title of their 1981 paper. Its radius is $\sim 34h^{-1}$ Mpc.

Martha Haynes, Ricardo Giovanelli and their friend Guido Chincarini began redshift surveys in 1982 based on observations of the 21 cm emission line of neutral hydrogen (Chincarini et al. 1983). Giovanelli and Haynes continued in subsequent years to make many seminal contributions to our knowledge of the neutral hydrogen content of galaxies and to the structure and nature of superclusters. One of the better examples of their redshift survey work is paper V in their series of eight papers on the Pisces-Perseus supercluster (Wegner, Haynes and Giovanelli 1993).

The CfA galaxy redshift survey reached full stride by the mid-1980’s when this group began to push deeper than $m = 15$. The first dramatic CfA results came with the publication of de Lapparent, Geller and Huchra (1986), a wide angle survey to $m = 15.5$. Figure 4a is a plot of the data used by de Lapparent et al. 1986. For comparison sake, Figure 4b is the same cone diagram with an overlay added showing the Gregory and

Thompson (1978) survey area.

4. SUMMARY STATEMENT ON THE EARLY REDSHIFT SURVEY WORK

IAU Symposium No. 124 entitled “Observational Cosmology” was held in Beijing, August 25-30, 1986. Allan Sandage gave the invited opening presentation. In his presentation, Sandage (1987) says the following about the early redshift survey work:

Gregory and Thompson (1978) “marks the discovery of voids, which have become central to the subject [of the large scale structure]. Prior work by Einasto et al. (1980 with earlier references), Tift and Gregory (1976), and Chincarini and Rood (1976) foreshadowed the development, but the Gregory and Thompson discovery is generally recognized as the most convincing early demonstration. Rapid developments in the mapping of various filaments and voids include the studies of Tarenghi et al. (1979), Gregory et al. (1981), Kirshner et al. (1981), Gregory and Thompson (1984), Chincarini et al. (1983), and Huchra et al. (1983). A general review is given by Oort (1983).”

IAU Symposium No. 124 was held immediately after the the March 1, 1986, publication of the paper by de Lapparent, Geller, and Huchra (1986) showing the “Coma stickman” in the center of the CfA cone diagram (Fig. 4).

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TABLE 1
REDSHIFT SURVEY TIMELINE

Authors	Citations	3D Plot	Description
Chincarini & Rood 1971	107	...	Perseus cluster virial analysis
Chincarini & Rood 1972a	78	...	Perseus, Cancer, Coma, A2197/9
Chincarini & Rood 1972b	46	...	Coma, A2197/9, NGC4272
Tift & Gregory 1973	21	...	Coma redshift data only
Tift, Jewsbury, Sargent 1973	16	...	Cancer cluster virial analysis
Chincarini & Martins 1975	18	...	Seyfert Sextet redshifts
Tift & Tarengi 1975a	25	...	A1367 velocity dispersion
Tift & Tarengi 1975b	30	...	Coma radio galaxy redshifts
Tift, Hilsman & Corrado 1975	19	...	NGC507 cluster virial analysis
Chincarini & Rood 1975	42	radial	Survey 14.2° W of Coma.
Tift & Gregory 1976	135	cone	Coma $r=6^\circ$ "devoid" foreground
de Vaucouleurs et al. 1976	2nd RCBG
Chincarini & Rood 1976a	87	radial	Survey 14.2° W of Coma. Noticed a "segregation of redshifts".
Chincarini & Rood 1976b	29	radial	Pegasus I & II redshift survey
Tift & Tarengi 1977	14	...	Redshifts of Coma radio galaxies
Davis, Geller & Huchra 1978	82	...	$m=13.0$ mean mass density only
Gregory & Thompson 1978	305	cone	Coma/A1367 $11^\circ \times 23^\circ$ to $m=15.0$ Discovered voids with $r > 20h^{-1}$ Mpc
Joeveer, Einasto & Tago 1978	114	cone	Found "large holes" in $70^\circ \times 70^\circ$ area
Tarengi, Tift, Chincarini, Rood & Thompson 1979	127	cone	Hercules redshift survey with void in foreground
Tarengi, Chincarini, Rood & Thompson 1980	90	cone	Hercules supercluster analysis
Gregory, Thompson & Tift 1981	173	cone	Perseus supercluster with large voids
Chincarini, Thompson & Rood 1981	57	cone	$44h^{-1}$ Mpc filament Hercules to A2197/9
Selected Second Wave Papers			
Kirshner, Oemler, Schechter & Shectman 1981	413	...	$35^\circ \times 35^\circ$ sparsely sampled to $m=16.3$. Bootes void $r=34h^{-1}$ Mpc
Davis, Huchra, Latham & Tonry 1982	241	cone	$m=14.5$ north of $\text{Dec}=0^\circ$
Einasto, Joeveer & Saar 1980	166	...	Overview of large scale structure
Chincarini, Giovanelli & Haynes 1983	39	...	HI redshifts Coma/A1367 bridge
de Lapparent, Geller & Huchra 1986	772	cone	$6^\circ \times 117^\circ$ survey to $m=15.5$
Wegner, Haynes & Giovanelli 1993	69	cone	Pisces-Perseus supercluster

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