SUPERCLUSTERING AND SUBSTRUCTURES

Guido Chincarini
European Southern Observatory, Garching, West Germany,
and University of Oklahoma

The history of the Universe is infinitely more interesting than the history of the study of the Universe.

- Zel'dovich and Novikov (1983) -

PROLOGUE

The understanding we have today of the distribution of galaxies resolves some of the debates which were going on in the seventies. Future data and analysis may allow us to discriminate among cosmological models.

In 1972, Zwicky was convinced, as a result of his work with the Schmidt telescopes (Palomar 18 inch and 48 inch), that the Coma Cluster of galaxies had to be much larger(1) than the 100 minutes of arc estimated by Omer et al. (1965). In his conception of the distribution of galaxies, very large clusters were tenuously connected and superimposed on a uniform background of galaxies.

The problem of the "discrepant" redshift in groups (for instance, the Stephan quintet and Seyfert sextet) was already known to us (see also Zwicky, 1957) and the reality of the Local Supercluster (see de Vaucouleurs, 1983) was not exempt from objections.

Work directed at understanding these, and related cluster problems, (Chincarini and Martins, 1975; Chincarini and Rood, 1975) led to the finding of the segregation of redshifts in cluster and non-cluster regions and to the concept that galaxies, and clusters, were part of very large structures. Regions void of galaxies were detected together with the irregular structures (Chincarini and Rood, 1976; Gregory and Thompson, 1978; Tarenghi et al., 1979; Kirshner et al, 1983). A question asked at a brown-bag lecture at Harvard (1975/1976) and at a meeting in

(1) In <u>Morphological Astronomy</u> Zwicky (1957) estimates a diameter of 320 minutes of arc from the 18-inch Schmidt observations and of at least 12° from the 48-inch Schmidt data.

M. Capaccioli (ed.), Astronomy with Schmidt-Type Telescopes, 511–526.

Rome by Rees (1976) on the statistical significance of the distribution in the redshift space, was better answered only later (Chincarini, 1978).

Fundamental surveys and studies existed which had been undertaken with the aim of understanding the distribution of galaxies. I refer in particular to the survey of clusters by Abell (1958), to the catalogue by Zwicky and collaborators (1961-1968) and, above all, to the careful counts of galaxies by Shane and Wirtanen (1967), and the related studies by Neyman, Scott and Shane (1953) and Scott, Shane and Swanson (1954). On this material, Peebles (1980 and references therein) developed the powerful "machinery" of the autocorrelation functions aiming 1) to understand the distribution of matter in the Universe and its implications and 2) to discriminate among cosmological models.

The IAU Tallin Symposium (1978) marks the acceptance of the new findings and stimulates further work. The Crete IAU symposium (1982) reflects the gain in new knowledge at all wavelengths allowing a broad discussion and intercomparison between theoretical and observational findings. By the time of the Crete meeting, among others, the extensive CfA survey by Davis et al. (1982) had also been completed.

The fast enrichment of knowledge we achieve through the work of capable scientists makes it exciting to be even a small part of all this. The flourishing of excellent work, the involvement of highly capable astronomers, and the recent publication of good reviews (see for instance Oort, 1983) make it difficult, and perhaps unnecessary, to make a new review of the field at this time.

In this lecture, therefore, I prefer to discuss only a few topics and show some preliminary results of the work in progress. The analysis I present is preliminary in the sense that the sample and statistics must be refined, and in a few cases we see improvements which must be made and are in progress. More important, the comparison with models is only in its infancy. It is appropriate, nevertheless, to discuss the work in progress at this time and location since new lines of developments may be suggested.

INTRODUCTION

What is meant by supercluster depends on the time and on the author. In all cases, however, it identifies a large agglomerate of something, clusters of galaxies, and/or galaxies, and in this sense it is synonymous with large scale structure. Its meaning is generally defined by the context in which it is used and it may be appropriate to avoid, at this time, a sharp definition and rather to leave it floating. It is part of the research which is in fact in progress to determine the statistical properties of these structures (nomen est numen). As an operational definition the reader may identify it with the concept of "clouds" as empirically defined by Shane and Wirtanen (1967), extended, however, to three dimensions.

Third order clustering is not yet observed and II order clustering is not meant to be characterized by clusters of clusters of galaxies, in the sense, for instance, that the Coma cluster is a cluster of galaxies. It is more accurate, perhaps, to talk of groups, up to 10-20 members, of clusters. Clusters are clumped as shown by Abell (1958) and, to mention only the latest work, by Bahcall and Soneira (1983a). The latter authors in fact show that clusters of galaxies are correlated over separations of about 100 h^{-1} Mpc ($h = H_0/100$) and define structures comparable in size to the one defined by the galaxies.

The observed distribution of galaxies is very clumpy and the agglomerations define large structures (no boundary has yet been found) of very irregular forms with density peaks which coincide with the clusters of galaxies. Such structures seem to be connected to each other and never seem to be isolated. This picture was proposed, based on some early observational evidence, by Chincarini and Rood (1980), suggested by the theory of Zel'dovich and colleagues (1978) and in a somewhat different form proposed by Einasto et al. (1978). In such a picture it would be strange to detect an isolated cluster of galaxies.

If positive density fluctuations form from a homogeneous medium we expect (as the a posteriori logic suggests) negative density fluctuations, that is, regions where the density of galaxies is very low. Such regions have been observed (see, for instance, Chincarini and Rood, 1976; Tifft and Gregory, 1976; Chincarini, 1978; Kirshner et al., 1982). The perhaps unexpected result was that, so far, no galaxy has been observed in such voids. In this way, an upper limit can also be put on the density of an eventual "uniform background" of galaxies. The voids themselves assume a high cosmological significance because they characterize the high order correlation functions and allow tests between numerical models and observations.

Statistics on the voids may soon be available. The topology is stable and favoured by the passage of time because the positive and negative density fluctuations act in the same direction and tend to group the matter (for numerical and analytical discussion see Peebles, 1982, and Salpeter, 1983). One of the problems to be solved, observationally, is the determination of the density enhancement above which we have the formation of bound groups and clusters and below it unbound density enhancements. It is as yet somewhat unclear whether unbound groups, or clusters, have been observed (see, however, Gott et al., 1973).

The study of a fair sample of the Universe allows a determination of the density parameter Ω which is unaffected by non-observed mass in galaxies (flat rotation curves detected by Bosma, 1978, and Rubin et al., 1982) and by stability problems in clusters. The most recent determinations give Ω = 0.1-0.3 (Davis and Peebles, 1982; Bean et al., 1983).

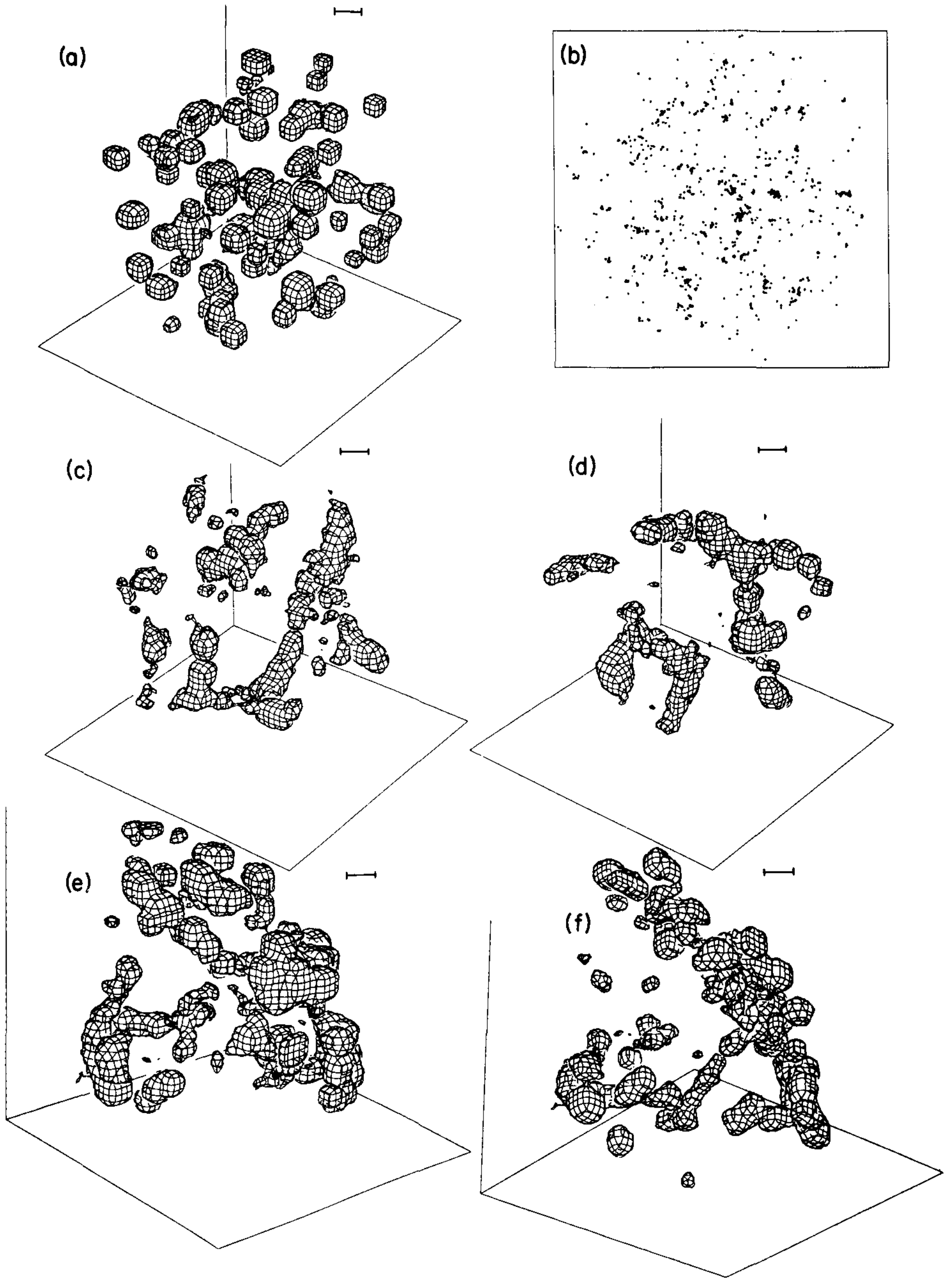

Figure 1. Comparison between the space distribution of numerical models and observations. (a) and (b) Poisson model, (c) and (d) pancake models (adiabatic) and (e) and (f) Center for Astrophysics Northern Survey. (From Frenk, White and Davis, Ap.J. 271, 417).

Is the above picture reflecting a hierarchical distribution? Do we have evidence of third order clustering? In fact, is the large correlation length estimated for clusters of galaxies an indication of III order clustering?

Shandarin (1983) and Frenk et al. (1983) show that in the adiabatic models, the correlation function $\xi(r)$ and the visual appearance of the structures match better than in other models (Poisson-isothermal) the observed distribution of galaxies (Figure 1). A large coherence length is theoretically demanded not only by models developing from primordial adiabatic fluctuations, but also by models in which the mass distribution in the Universe is dominated by neutrinos with non-zero rest mass (Bond, Efstathiou and Silk, 1980). In the very low density regions, voids, generated by adiabatic numerical models, galaxies may be unable to form. While the statistical reality of voids is not in doubt, we must be cautious (Peebles, 1983) in seeking their physical interpretation, since these can also be produced in a hierarchical process. Always following Peebles, the existence of voids does not mean that there is a reason to think that $\xi(r)$ has been underestimated on large scales. If the voids were produced by a physical process operating in a coherent way over scales $\sim 100\ h^{-1}$ Mpc, the process would have had to have operated in a peculiar way, leaving $|\xi| \ll 1$ on this scale. For arguments in this direction see also Soneira and Peebles (1978) and Bean et al. (1983). On the other hand, as we have seen, clusters give a larger correlation length.

In summary, we would like to evolve models to match the observed distribution, that is to go from a more homogeneous and isotropic past to the observed clumpy distribution (an expanding Universe is unstable against growth of departures from homogeneity and isotropy). To do this, we need to understand what we observe. Such an understanding will finally shed light also on the problem of the formation and evolution of galaxies as well.

The visual appearance may not be enough to discriminate between models. The autocorrelation functions are statistical descriptors able to average over the complexities of the structure to evidence the basic properties; they are, however, not sensitive to topological details which may be important. It seems worthwhile, therefore, to look into some properties of the structures (substructures) and possibly define some parameters and/or characteristics which allow a close comparison with models.

A WAY TO SELECT STRUCTURES: THE PERCOLATION (OR DENDROGRAM) ALGORITHM

The percolation algorithm in its most sophisticated developments is used in various branches of science and especially in solid state physics. It was imported into astronomy by Materne (1978) and used in selecting groups and applied to superclusters to define membership in the embedded clusters by Materne and others (see Appendix of Tarenghi et al., 1980). Gerola and Seiden (1978) used a similar technique in the stochastic study of the formation of spiral arms. Zel'dovich et al. (1982) and Shandarin (1983) demonstrate its usefulness in discriminating among numerical models and observations of the large scale structures.

In brief: The objects are considered "connected" if their separation is smaller than a preselected parameter R_i. A structure, let us say, at a level i, is the ensemble of all the connected points of the sample (Figure 2). The definition is independent of symmetry or smoothing and the computer follows the structures as we would site the details of a crack in a wall or water suddenly spreading in a dry creek. In a cristal an electric current would follow the path defined by the impurities. The method is equivalent to selecting a structure with density (number of galaxies per square degree or per Mpc^3) above a certain level.

While the matter is almost straightforward in two dimensions, complications arise when a magnitude limited sample is used. A minor and easily treatable inconvenience is that the presence of cluster virial velocities will cause spurious separations. A more difficult problem to treat is the distortion introduced into the geometry by a sample limited by apparent magnitude. This is especially true for large values of the parameter R_i which allow to probe larger regions of space. Due to the fact that we are probing at different absolute magnitudes and different distances, we ficticiously change the density of galaxies.

To take this into account we may use a value of R_i which is a function of the distance x. Since $N(x) \propto D(x)\ \Gamma\ (\alpha+1,\ L/L^*)$ where $N(x)$ is the density $D(x)$ corrected by the effect of the magnitude limited sample and

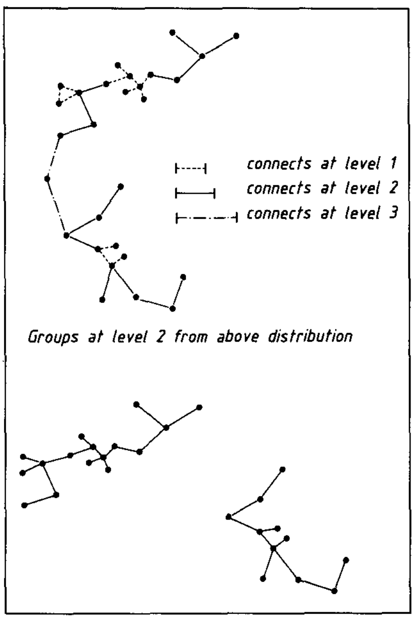

Figure 2. Connected ensembles at different levels for various levels of the parameter R. On the bottom of the figure the two structures isolated at the 2nd level.

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$L/L^* = \mathrm{dex}\,[0.4\ (M^1 - m_1 + 5 \log x + 25)]$ we can write:

$$R(x) \simeq 2\ (1/N(x))^{1/3}$$

or

$$R(x_1)/R(x_2) \simeq \left(\frac{D(x_1)}{D(x_2)}\right)^{1/3} \left(\frac{\Gamma(\alpha+1,\ L_1/L^*)}{\Gamma(\alpha+1,\ L_2/L^*)}\right)^{1/3}$$

There is naturally a simpler way and this has been used also by Einasto, Klypin, Saar and Shandarin (1983). That is, after an estimate of the cluster volume one can remove the virial velocities from the sample and assign distance velocities according to a "reasonable" model. Furthermore, instead of using an apparent magnitude limited sample, an absolute magnitude limited sample can be used. In this case, however, only part of the data are used. Here I prefer to use the whole sample.

STRUCTURES AND SUBSTRUCTURES

An analysis of the ESO/Uppsala catalogue showed the Hydra-Centaurus supercluster as the most prominent structure of the southern hemisphere. Such a structure may be connected to a filament evidenced by Moody et al. (1982) in their analysis of the Shane and Wirtanen catalogue, their filament N.13. The growth of the 3-dimensional clustering, as a function of the parameter R is reproduced in Figures 3 and 4 for the main structures in the region of Coma/A1367 and Perseus/Pisces.

The structures are rather extended in one dimension (note that the boundaries are defined by the region of the sky selected) and of the order > 100 Mpc while, especially in the Perseus-Pisces supercluster, the width and depth are of the order of 15-20 Mpc. Galaxies are, however, still "connected" in a redshift range of 4000-5000 km/sec. In addition to the main structure (or main structures when detected from a larger sample), substructures are also evidenced. Some of these have been reproduced in Figure 5.

For the main structure and a set of substructures with at least 5 members we have measured the length and width. In this case we called length the sum of the separations connecting the "first" point of the structure to the "last" connected point (see Figure 2), and width either the mean separation or the r.m.s. of the separation of the rest of the points from the segmented line defining the length. Following an analysis similar to the one by Zel'dovich et al. (1983), we also constructed the multiplicity function for the substructures isolated for various values of the parameter R in order to follow the growth of the structures as a function of R.

Comparison with a random distribution of points is needed to see a) whether the detected substructures are statistical fluctuations and b) whether or not some of the statistical properties of the observed filaments differ from those generated as fluctuations of a random

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ensemble. The same analysis, therefore, which was used for the observed redshift sample was applied to a sample of 2000 random points simulating a magnitude limited sample of objects in a volume of space similar to the observed volume. That is, we have the additional constraint

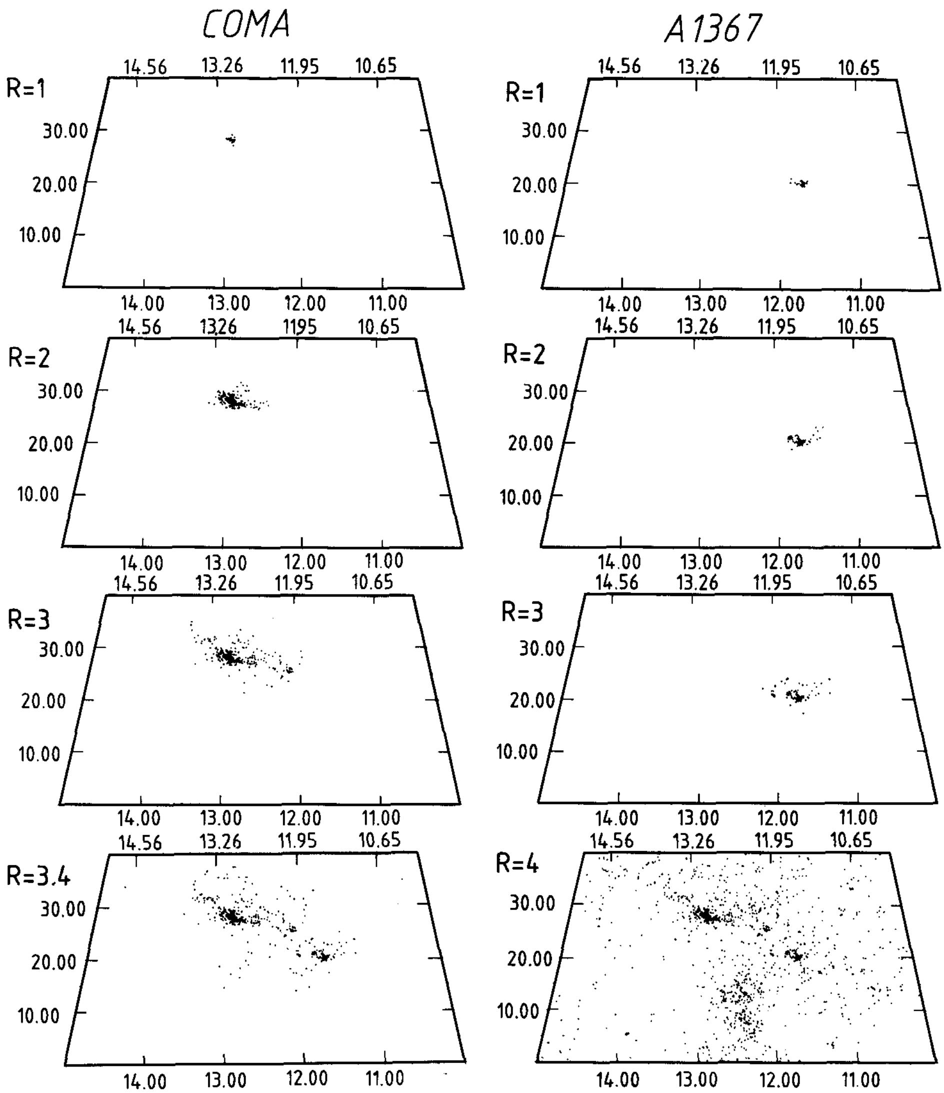

Figure 3. The growth (percolation in 3 dimensions) of the Coma/A1367 supercluster as a function of the parameter R. The fast connection to Virgo is partly spurious due to the use of an apparent magnitude limited sample. (R.A. in hours, declination in degrees.)

$$N(v_i,v_j) = \int_{x_i}^{x_j} x^2\, D(x)\, \Gamma\,(\alpha+1,\ L/L^*)\ /\ \int_0^{\infty} x^2\, D(x)\, \Gamma\,(\alpha+1,\ L/L^*)\ .$$

The substructures detected in the random sample do not differ noticeably from the real structures. A sample of the former is reproduced in Figure 6. In Figure 7 we have the distribution thickness/length (thickness and length as defined above) at some value of the parameter R, both for the observations and for the random sample. The distributions are very similar, a matter which may be only partly due to our definition of length and width. A better discriminator seems to be the maximum length of the connected region as a function of the parameter R (Zel'dovich et al., 1982).

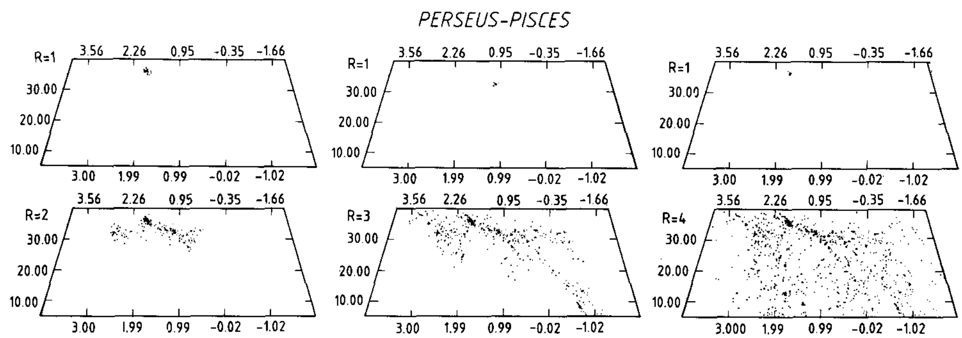

Figure 4. Same as in figure 3 for the Perseus-Pisces sample. Note the filament extending toward Pegasus.

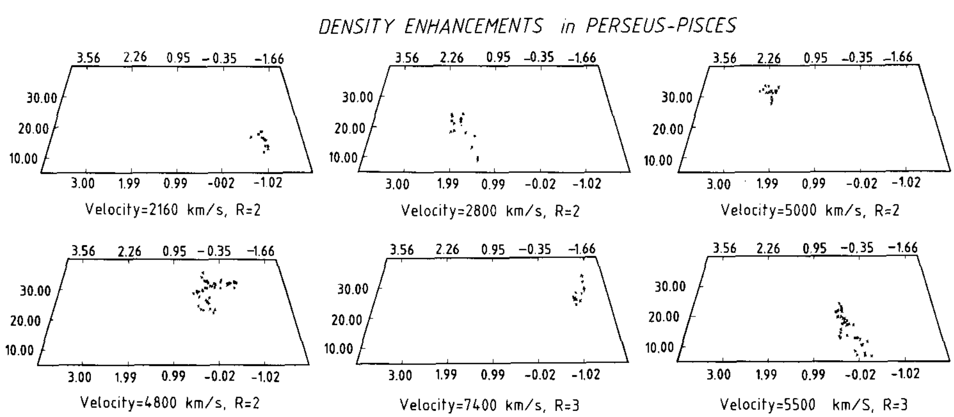

Figure 5. Substructures detected by the percolation algorithm in the Perseus-Pisces sample. The approximate mean velocity of the group is also given.

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What characterizes a real structure, however, is its stability to variations of the parameter R. A set of structures detected in the random sample at some value of R disappears in the background for a different value of R, at which value a new set of substructures will appear. Structures which are "stable" in the observed sample will preserve their identity as a function of R. To some extent it is similar to the "stability" of a density perturbation. Differences between the random and observed samples are also detected in the variations of the multiplicity function as a function of values of the parameter R (Figure 8). In Figure 8 such variations have been reproduced for the Coma extended region, the random sample and the Perseus/Pisces sample. At large values of R in all cases we form a main "agglomerate" and some distribution of smaller

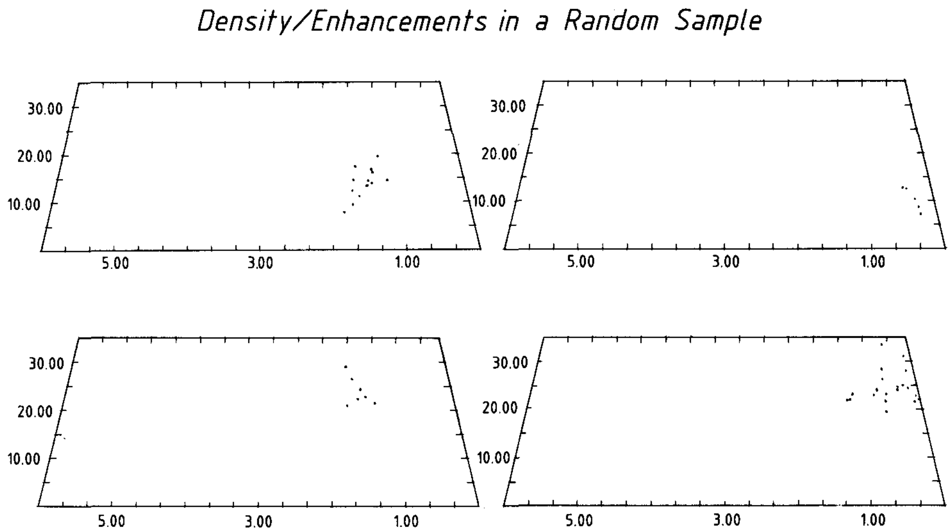

Figure 6. Substructures detected by the percolation algorithm in a random (apparent magnitude limited) sample of 2000 points.

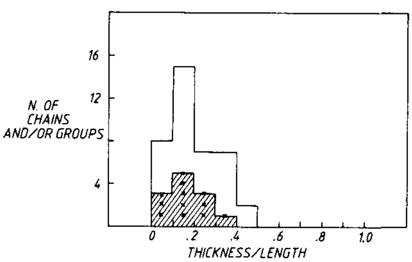

Figure 7. Distribution of the ratio thickness/length in the observed and random sample obtained for substructures (with more than 5 members) at some value of the parameter R.

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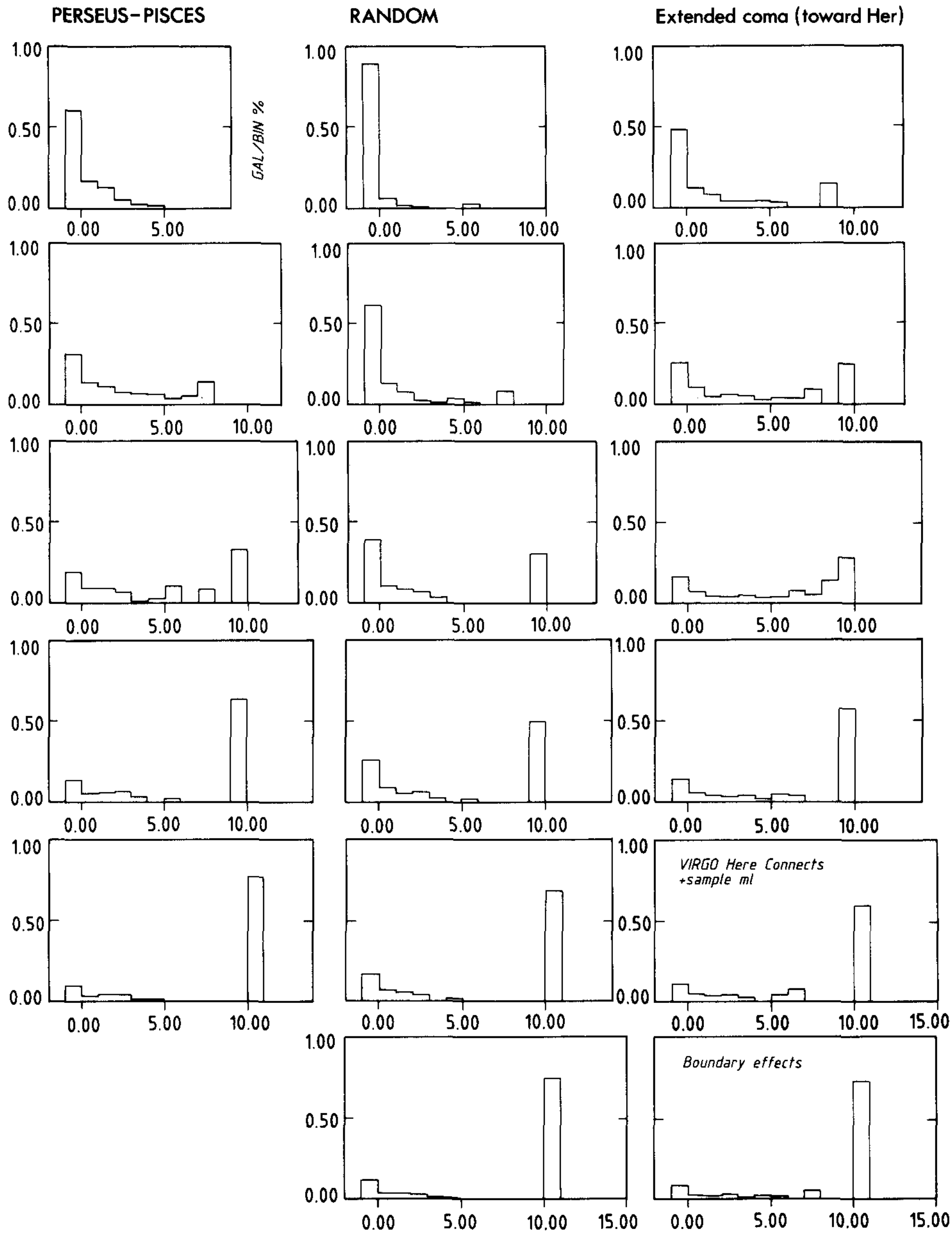

Figure 8. Variation of the multiplicity function, % of galaxies per ensemble of various richness (richness in bin of $\log_2 N$), as a function of the parameter R. The random sample does not form intermediate clustering and the substructures are unstable (lose their identity) to variations of the parameter R. All the substructures have been detected, and the number of members counted, using the percolation algorithm. At large R, with the samples used, we have boundary effects and the connection (in part spurious) to Virgo.

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groups. The main difference consists in the early development, where the random sample never develops a sizable number of intermediate richness clusters.

The conclusion is that the majority of the observed substructures of the real world are "stable" and are not statistical fluctuations. They are not due to the unknown mechanism by which the eye picks out textures and patterns. Such structures can be isolated and their topology, and, perhaps, kinematics, measured. In a simple way, it is a matter of contrast as expected.

An extreme example given in Figure 9 is the filament selected in the Pegasus region, extending between 5° and 25° declination. The tip of this

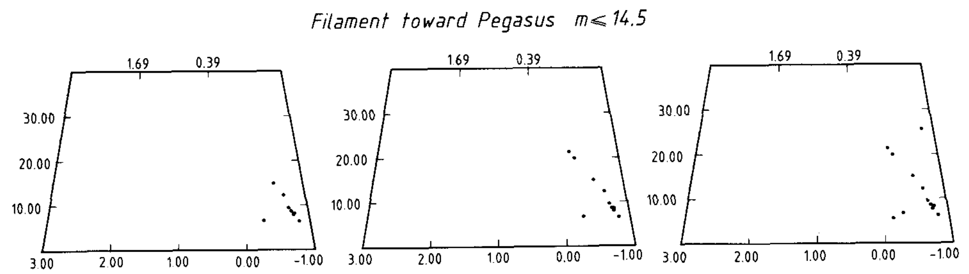

Figure 9. The filament in Pegasus, m < 14.5.

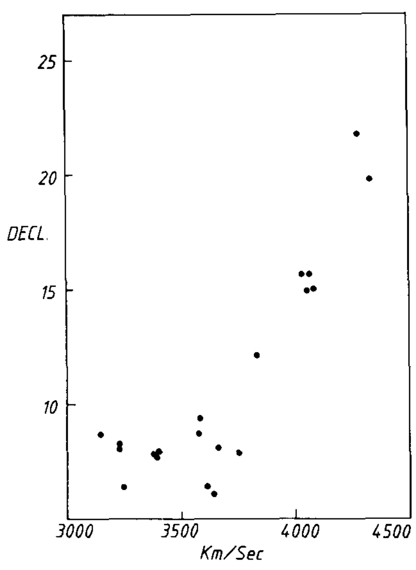

Figure 10. The filament in Pegasus in the declination-redshift plane.

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very narrow filament points away from us as can be seen from Figure 10 where the objects are plotted in a declination redshift diagram.

Such substructures may be difficult to generate in isothermal (Poisson) models and may finally argue against a hierarchical Universe.

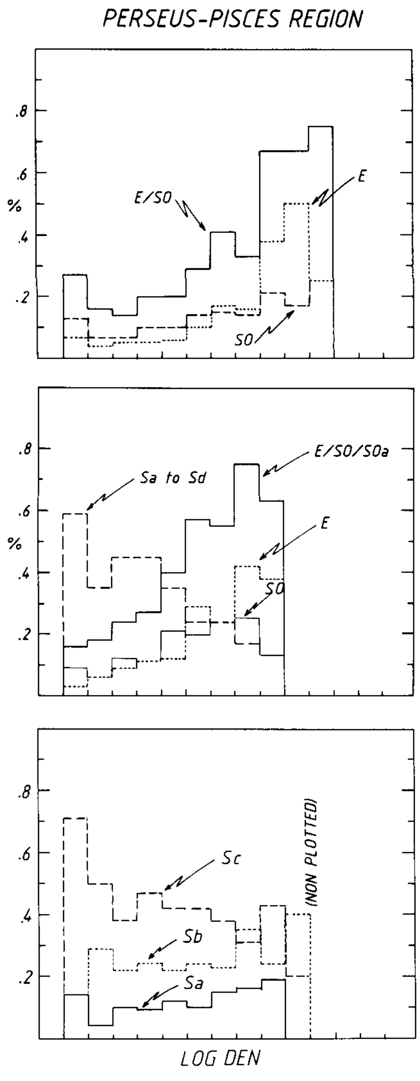

Figure 11. Distribution of types in the Perseus-Pisces sample as a function of surface density of galaxies.

MORPHOLOGICAL SEGREGATION

Giovanelli, Haynes and Chincarini (1983) noticed that in the region of the Perseus-Pisces galaxies are somewhat segregated according to their morphological type (see fig. 16 in Oort, 1983).[2] The distribution of galaxies is indicative of a correlation between morphological type and density. Such correlation is illustrated in Figure 11.

The result, which is being tested in other regions of space, stresses the fact that type segregation is a phenomenon which extends to very low density regions of space. In the sample considered here, the density ranges, for galaxies with $m < 14.5$, from a maximum of about 3.7 galaxies per square degree (note that the Perseus cluster, A426, is outside the sample area) to a density of about $1.7\ 10^{-3}$ galaxies per square degree. Such segregation is visible in various low density filaments (substructures) as well, where a preponderance of spiral is observed, a fact evidenced also by Focardi et al. (1983) in other samples.

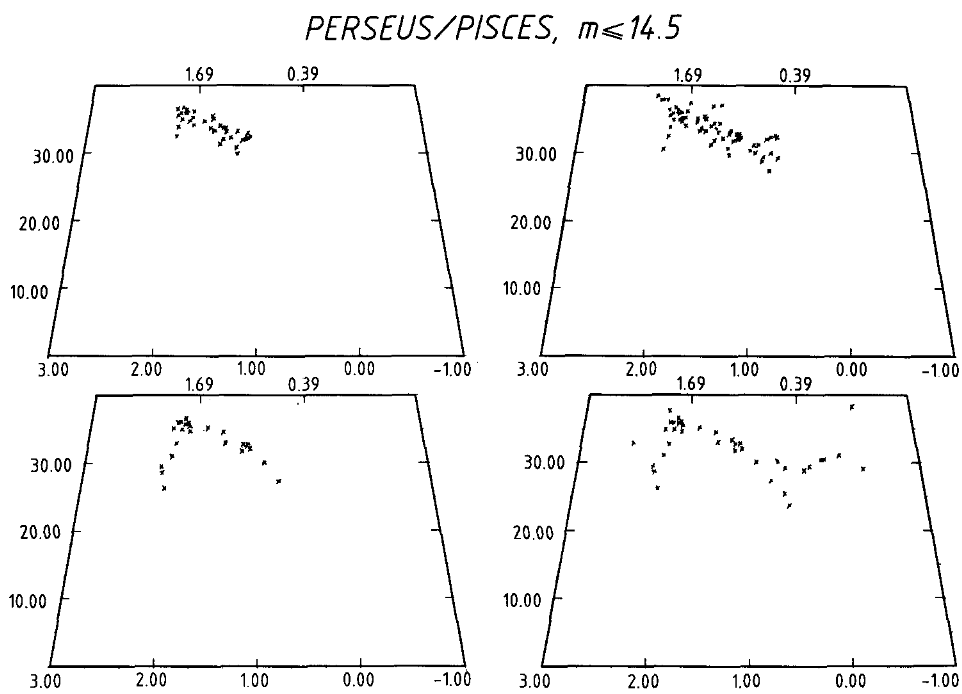

Figure 12. The main structure detected, using the percolation algorithm, in a magnitude limited subsample, $m < 14.5$, of elliptical and spiral galaxies. The pattern of the elliptical galaxies (similar to the pattern of spirals) cannot be generated by galaxies which evaporate from clusters. If a merging mechanism of formation is at work it should act locally and during the collapse phase (if any) of the filaments.

(2) A similar effect was evidenced by Tarenghi et al. (1980) in an early version of the Hercules paper. Because of the low statistical significance of the effect the statement was modified following the referee's comments. Compare, however, their figure 11, top and bottom.

As has been mentioned already this is suggestive of a formation mechanism in which the morphological type is somewhat conditioned by its environment with little, if any, evolution along the Hubble sequence. The merger mechanism (see, for instance, Silk and Norman, 1981) is very attractive. However, it is doubtful that ellipticals in the low density regions may be the result of cluster evaporation, as is demonstrated by their distribution in Figure 12. Are such patterns understood in the framework of a hierarchical Universe? We are eager to proceed with our work and further simulations, confident to gain further understanding on this matter.

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