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THE DYNAMICS AND EVOLUTION OF CLUSTERS OF GALAXIES

GRANT NAGW-201

Semiannual Report No. 11

For the period 1 July 1986 through 31 December 1986

Principal Investigators

Dr. Margaret Geller and Dr. John P. Huchra

January 1987

Prepared for
National Aeronautics and Space Administration
Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
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Over the period covered by NAGW-201 we have undertaken a broad program of research with the long-range goal of producing a coherent picture of the formation and evolution of large-scale structure in the universe. The program can be divided (with fuzzy boundaries) into projects which examine (1) the relationship between individual galaxies and their environment, (2) the structure and evolution of individual rich clusters of galaxies, (3) the nature of superclusters, and (4) the large-scale distribution of individual galaxies. The four sections of this report are brief reviews of results in these areas. References to papers supported by NAGW-201 are indicated by *.

1. Galaxies and Their Environment

The striking qualitative difference between the population of galaxies in low and high density regions has been recognized for a long time (Hubble and Humason 1931). In magnitude llimited samples, spiral galaxies dominate the low density "field" and ellipticals and S0's dominate the densest regions of rich clusters.

The physical origins of this relationship between galaxy morphology and environment remain debatable (see Dressler 1984). The fundamental issue is the relative role of nature (conditions at or shortly after the epoch of galaxy formation) and nurture (interactions of a galaxy with its environment at more recent epochs). Ram pressure stripping, accretion, tidal stripping, galaxy mergers, and galactic cannibalism are some of the environment-dependent processes which have been suggested. All of these processes along with the set of initial conditions conspire to produce the rather gentle variation of galaxy morphology with *local* density. Dressler (1980) first derived the relation from his sample of rich clusters; later Postman and Geller (1984)* used the CfA redshift survey (Huchra *et al.* 1982) to extend the relationship to lower densities and to show that it applies to the general field. The relation extends over 6 orders of magnitude in space density. In regions where the dynamical timescale ($t \sim (G\rho)^{-1/2}$) is (assuming a charactersitic mass-to-light ratio of $\sim$ 400) $\gtrsim H_0^{-1}$, there is no dependence of morphology on density. At densities $\gtrsim$ 600 galaxies Mpc^{-3}, S0's dominate the galaxy population. At densities $\gtrsim$ 3000 galaxies Mpc^{-3}, the fraction of ellipticals rises steeply. In these regions the collapse time is short compared with the Hubble time and short compared with the $\sim 10^9$ years required for disk formation. This qualitative physical argument which links morphology to the local dynamical timescale favors the importance of environment over initial conditions.

Galaxies of different morphology often do not share the same velocity distribution. In the Virgo cluster the spirals have an apparently larger velocity dispersion than the ellipticals. Interpretation of this result is complicated by the spatial structure of the cluster (Huchra 1985)*. The dependence of the velocity distribution on the galaxy morphology can provide a measure of the relationship between dynamical history and morphology. The derived orbit distribution for galaxies of a particular morphology determines the environment the galaxy sees.

There are preliminary indications that the properties of individual galaxies are also related to the large-scale structures revealed by redshift surveys. For example, the galaxies detected in the IRAS survey lie in the shell-like structures which surround voids in the CfA redshift survey extension (Huchra 1986; de Lapparent, Geller, and Huchra 1986)*; all of the IRAS sources lie well outside the dense core of the Coma cluster.

2. The Structure of Rich Clusters of Galaxies

N-body simulations show that detailed studies of individual rich clusters of galaxies can provide clues to the formation and evolution of these systems. The structure oı rich clusters also constrains the relative distribution of galaxies and dark matter. On a larger scale, the extension of the CfA redshift survey indicates that the structure of rich clusters may be intimately tied to the associated large-scale structure.

The sharpening of physical questions about clusters of galaxies is accompanied by an advance in our ability to obtain the spectroscopic and photometric data required to answer the questions. The number of detailed studies of custers is increasing rapidly.

In Dressler's (1980) sample of 65 clusters, 40% show more than one statistically significant peak in the surface number density of galaxies (Geller and Beers 1982)*. The uncertainty in the fraction of clusters with subcondensations is large because the biases in the selection of samples of clusters may be large and because the detection of structure in a particular cluster is limited by the number of galaxies in the survey. Nonetheless, the analysis of Dressler's sample shows that many clusters of galaxies (even systems as dense as Coma) are dynamically "young"; they retain the clumpy structure which is present in N-body simulations at early stages in the cluster evolution.

Even dense systems like A754 have detectable substructure (Fabricant *et al.* 1986)*. This cluster is as dense as Coma. A detailed analysis of the available x-ray and optical data shows that the system is (at least) bimodal. A model which consists of two self-gravitating isothermal spheres is consistent with both the optical and x-ray maps.

Simple two-body dynamical models can provide some insight into the history of double systems like A754 (Geller 1984)*. Application of the timing argument previously used to study the Local Group (Peebles 1971; Gunn 1974) yields an estimate of the probability that the components of these clusters form a bound system. The model indicates that systems like A754 are either about to coalesce or they are near maximum expansion. The N-body simulations of Cavaliere *et al.* (1986) produce systems which look remarkably like A754; the models predict that a significant fraction of clusters as massive as Coma (A754 is a case in point) should be near maximum expansion now; the dynamical evolution of these systems is slowed by the formation and persistence of substructures. The clumpiness we observe now is a result of the discreteness of the galaxies during the early stages of cluster evolution.

These systems muddy the distinction between clusters and superclusters. The usual distinction is a matter not only of physical scale but also of dynamical state. Superclusters are unrelaxed structures without symmetry or central concentration. These double clusters *are* then superclusters (Geller 1984)*.

3. Superclustering

There are two approaches to the general issue of the clustering of rich clusters: (1) the extraction of general statistical properties from cluster catalogs and (2) the study of individual systems.

We recently completed two extensive analyses of the statistics of the distribution of rich clusters (Postman, Huchra, Geller, and Henry 1985; Postman, Geller, and Huchra 1986)*. We confirmed the dependence of the cluster-cluster correlation function on richness originally claimed by Bahcall and Soneira (1983). We also show that in the range where the selection criteria of Abell and Zwicky overlap, the cluster correlation functions for the two catalogs agree. We emphasize a number of important selection effects in cluster catalogs which could affect the correlation function results.

The spatial correlation function for rich clusters measured by Bahcall and Soneira (1983) is derived from a sample which is dominated by the Corona Borealis supercluster. As part of his Ph.D. thesis research, Marc Postman (supported by a NASA graduate fellowship) studied this system (Postman, Huchra, and Geller 1986b; Postman, Geller, and Huchra 1987)*. We have measured more than 200 redshifts in six 0.75 square degree probes distributed over an $\sim$ 25 square degree region. Figure 1 shows the galaxy distribution in the region of the probes (outlined by solid lines).

Perhaps the most interesting result of the Cor Bor survey is the similarity between the redshift distribution in the region and the distribution in the Boötes region studied by Kirshner, Oemler, Schechter, and Shectman (1986). Figure 2 shows the redshift distributions. The void in front of the Cor Bor supercluster is separate from the famous void in Boötes but is in nearly the same redshift range. This sort of very long-range correlation is expected if the galaxy distribution has the general structure revealed by the CfA survey with voids of a characteristic size in the 30-50 Mpc range.

We have also studied the dynamics of the Cor Bor system. If the mas-to-light ratio on the scale of the entire supercluster ($\sim$ 13 Mpc) is the same as the mass-to-light ratio characteristic of the cores of the 6 rich clusters in the system, the supercluster is bound. The system dynamics can be explained *without* requiring an increase in mass-to-light ratio from cluster to supercluster scales.

4. The Large-Scale Distribution of Galaxies

Mapping out the large-scale distribution of individual galaxies is a step toward understanding the origin and evolution of large-scale structure in the universe. Over the past few years, each new approach to this problem has uncovered unexpectedly large structures. The 21-cm surveys by Giovanelli and Haynes (1985) and Giovanelli *et al.* (1986) defined the Perseus-Pisces chain. Optical surveys in deep probes uncovered the void in Boötes (Kirshner, Oemler, Schechter, and Shectman 1981; 1986). The completion of the first slice of the Center for Astrophysics redshift survey extension (de Lapparent, Geller and Huchra 1986)* suggests that galaxies are on thin, sharply defined surfaces which surround vast empty voids — a "bubble-like" structure.

The sequence of recent discoveries proves the power of redshift surveys. However, the volumes completely surveyed are at best comparable with the scale of the largest known inhomogeneities. The Shane-Wirtanen map (Shane and Wirtanen 1967; Seldner, Siebers, Groth, and Peebles 1977) remains the only sample of the universe which is large enough to examine the "typical" behavior of the galaxy distribution on large scales. There are two aspects of the map which have attracted particular attention. The filamentary appearance of the map has been one of the drivers for detailed calculations of the evolution of structure in the "pancake" or adiabatic picture for large-scale structure formation. The feature at 2.5°in the galaxy correlation function derived from the map (Groth and Peebles 1977) has been interpreted as a consraint on the universal mean mass density Ω, an indication of the transition between linear and non-linear clustering regimes, and as a reflection of the initial spectrum of fluctuations.

Because of the importance of the Shane-Wirtanen counts, we reexamined the data (Geller, de Lapparent, and Kurtz 1984; de Lapparent, Kurtz, and Geller 1986; Geller, de Lapparent, and Kurtz 1986)*. We found that systematic errors in the data affect the appearance of the map as well as the behavior of the angular correlation function at large scales. The filamentary appearance of the map is related to the pattern in which Shane and Wirtanen counted plates; variations in the counting efficiency of the two observers introduces large-scale features in the map. The break in the correlation function at 2.5°is indistinguishable from an artifact introduced by these same plate-to-plate variations. From the analysis of systematic variations in the counts, we derived limits which must be met by future surveys which are designed to measure the large-scale behavior of the correlation function. At the depth of the Shane-Wirtanen counts ($m_{B(0)} = 18.7$), the systematic errors must be limited to 5% on a scale of 2.5°. Even with the best modern techniques, these limits are not easily met.

The completion of the first strip of the CfA redshift survey extension yielded the most exciting results of the 1984-1986 period (de Lapparent, Geller, and Huchra 1986)*. Figure 3 shows the striking structure in the strip which covers $6° \times 117°$on the sky. The effective depth of the survey is $\sim$ 100 Mpc. This new survey contains 1100 galaxies. The Coma cluster lies at the center of the survey — it is the "torso" of the "homunculus".

The distribution of galaxies in the redshift survey slice looks like a slice through suds in the kitchen sink: the galaxies are on the surfaces of bubble-like structures with diameters of 25-50 Mpc. The topology poses serious challenges for current models of the formation of large-scale structure. One promising model for making the structures in the survey is the explosive galaxy formation theory of Ostriker and Cowie (1981) in which galaxies form in expanding shock fronts.

The shell-like structures may provide a clue to the relationship between galaxies and clusters of galaxies as tracers of the large-scale matter distribution in the universe. The appearance of the Coma cluster at the intersection of several shells provides a clue to the relationship which we will explore more fully as the survey covers a larger and larger volume. In a toy model with close-packed bubbles of fixed size and with clusters located at the interstices between bubbles, the typical separation of clusters is equal; to the radius of the bubbles. It is entertaining that the radius of the largest void in the survey, 25 Mpc, is the same as the mean separation of Abell clusters.

Another limit on the models may come from the relative distribution of galaxies as a function of surface brightness (Davis and Djorgovski 1985; Bothun *et al.* 1985). Biased cold dark matter models predict that low surface brightness galaxies should be less clustered than their higher surface brightness counterparts. Because redshift surveys are based on magnitude limited samples, it is hard to address this question directly; it is easier to examine the distribution as a function of luminosity. Comparison of the CfA survey complete to $m_{B(0)} = 14.5$ with the extension indicates that the galaxy distribution is independent of luminosity for $M_{B(0)} \lesssim -17.4$. The surveys of the Cor Bor region mentioned in the preceding section incidentally pass through the large shell which stretches from 13^h30^m to 17^h at 10,000 km s^{-1}(Figure 3). The shell and the enclosed void are apparent in the deeper probes and the structure is independent of luminosity.

The structures in Figure 3 extend as expected into the adjacent slice (Geller, Huchra and de Lapparent)*. It is sobering that the largest structures we see in the total survey (which now covers 12°× 117°to $m_{B(0)} = 15.5$) are the largest we can detect within the constraints imposed by the boundaries of the survey. The size of the inhomogeneities relative to the extent of redshift surveys may underlie unexplained variations in the determination of traditional statistics of the distribution like the luminosity function and the correlation function (particularly at large scale).

The "bubble-like" structures suggest a new set of measures for comparing the data with the simulations (de Lapparent 1986). The thinness and coherence of the structures are important tests. The distribution of voids, particularly of the largest ones provides another constraint. The determination of the large-scale end requires deeper surveys which are underway and funded by the current incarnation of NAGW-201.

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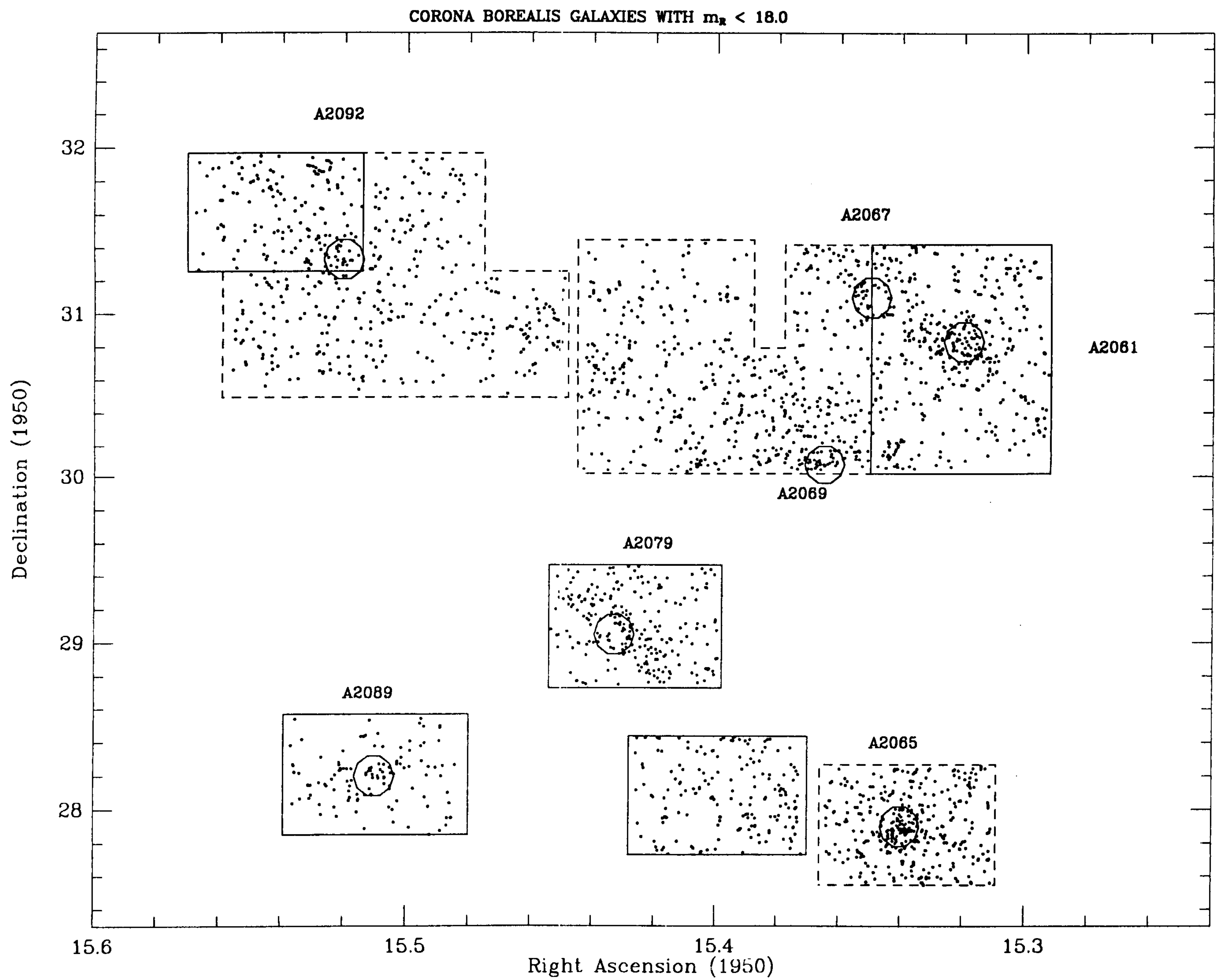
CORONA BOREALIS GALAXIES WITH m_R < 18.0
A2092
A2067
A2061
A2069
A2079
A2089
A2065
32
31
30
29
28
Declination (1950)
15.6
15.5
15.4
15.3
Right Ascension (1950)

Figure 1

Figure 4a (TOP) *Figure 4b (BOTTOM)*

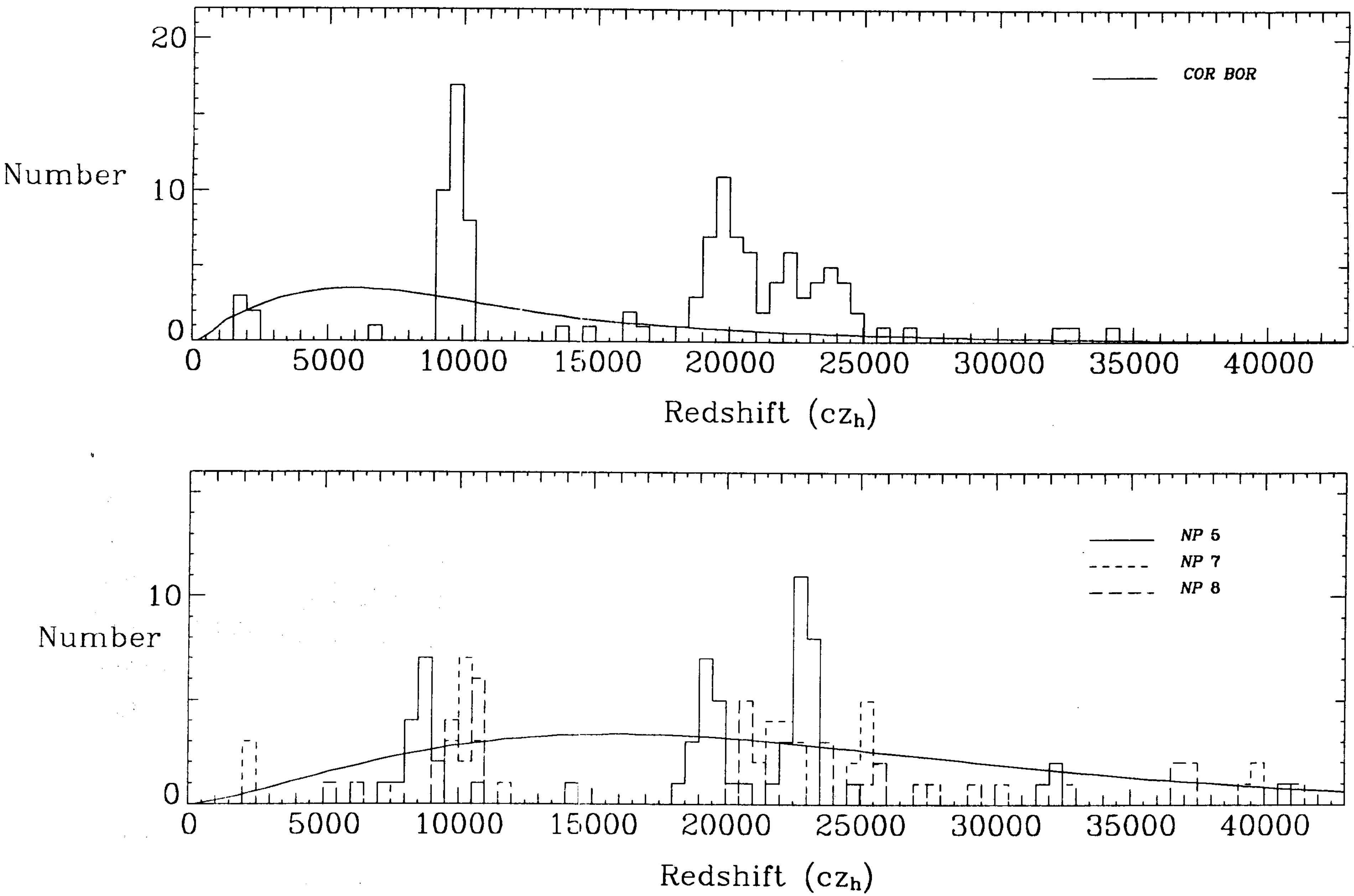

Figure 2

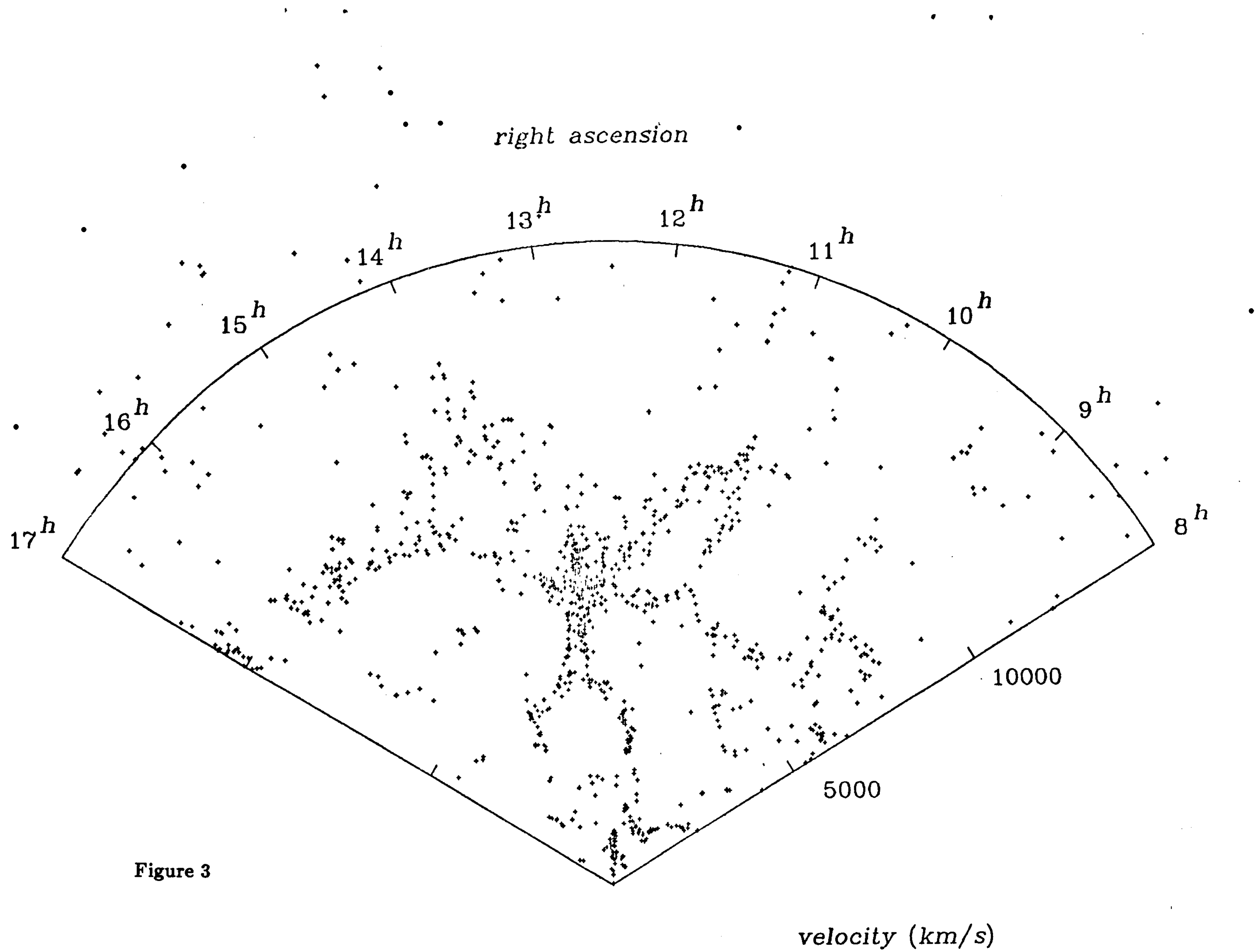
right ascension
17 h
16 h
15 h
14 h
13 h
12 h
11 h
10 h
9 h
8 h
10000
5000
velocity (km/s)

Figure 3