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NEARBY GALAXY REDSHIFT SURVEYS

(Invited Talk)

Paulo S. Pellegrini and L. Nicolaci da Costa

CNPq/Observatório Nacional, Brazil

ABSTRACT. The most important results of the wide-angle redshift survey of galaxies carried out in the Southern Hemisphere (SSRS) and its extensions are reviewed and compared to those of the CfA Survey. Here we emphasize the interpretation of the data as challenges to different scenarios of galaxy formation with dark matter. The definition of a fair sample of the Universe with the presently available databases is also discussed.

RESUMO. Os resultados mais importantes do levantamento de velocidades radiais de galáxias realizado no Hemisfério Sul (SSRS) e suas extensões são apresentados e comparados com os do levantamento realizado pelo CfA, dando ênfase à interpretação dos dados como testes para diferentes cenários de formação de galáxias com matéria escura. A definição de uma amostra representativa do Universo com os dados atualmente disponíveis é também discutida.

Key words: **CLUSTERS-GALAXIES – COSMOLOGY – GALAXIES-FORMATION**

INTRODUCTION

An impressive increase in the number of galaxy radial velocity determinations occurred in the last fifteen years, specially in the last decade. This number was about 2700 in the mid 70's, as can be inferred from the catalog prepared by de Vaucouleurs et al. (1976, RC2), while nowadays the compilation being carried out by John Huchra (1989) comprises more than 31000 galaxies. This increase is a consequence of the effort by several groups working on extragalactic astronomy, stimulated by the increasing interest on the study of large scale structures and by the technological development that allowed the construction of efficient detectors.

On the other hand, theoretical aspects of galaxy formation have been investigated for a long time ago, leading to, at least, two major competing scenarios for gravitational clustering. Roughly speaking, the formation of galaxies and large structures can be understood assuming that primordial small adiabatic perturbations in a homogeneous, isotropic and flat Universe, evolve under the action of their own gravity, "detaching" from the Hubble expansion and collapsing. The dark matter component of the Universe, which is believed to constitute 90% of its total mass, plays an important role in this process, since its perturbations evolve continuously during all eras, forming localized potential wells that will act as "seeds" for galaxy formation. The baryonic matter perturbations, which are damped or frozen during the radiation-dominated era (stagspansion), fall dissipatively after recombination into the "seeds" forming the galaxies and large structures we see.

Hot dark matter, relativistic when entering the horizon (e.g. neutinos of mass $\approx$ 30 eV), has its initial mass spectrum truncated for smaller masses (due to free streaming) and gives origin to systems of 10^{14} to 10^{15} $M_{\odot}$, that collapse into "pancakes" (supercluster), that later fragment, forming galaxies. Cold dark matter, which is non-relativistic when entering the horizon (e.g. axions) has a smooth initial mass spectrum with more power at smaller masses and forms, at first, systems of $\approx$ 10^6 $M_{\odot}$, that hierarchically form galaxies and superclusters. Some texts describing and discussing these scenarios in detail and their theoretical and observational implications are presented by Peebles (1980), Efstathiou and Silk (1983), Primack (1986) and Blumenthal (1987). Alternative processes of galaxy formation such as the explosion scenario (Ostriker and Cowie 1981), cosmic strings (e.g. Turok 1987) and domain walls (e.g. Ryden 1989) were not yet fully developed to confront the observations.

THE SURVEYS AND THEIR MAIN RESULTS

The observed distribution of galaxies and its clustering properties (e.g. Geller 1987) must, somehow, preserve the imprints of its formation processes, and a fair sample of the Universe should, in principle, be able to reveal them. Basically, the attempts to obtain samples for analyses can be divided into three types: a)- surveys covering a specific structure, b)- deep, beam-like surveys and c)- shallow or moderately deep surveys, covering a wide angular extent. In the first case, is the effort of Haynes and Giovanelli (1988) to map the Perseus-Pisces Supercluster and Dressler's (1988) Supergalactic Plane Redshift Survey covering the region of the "Great Attractor" and in the second, the works of Kirshner et al. (1987) that led to the discovery of the Bootes void and that of Broadhurst et al. 1990. Only wide angle surveys will be discussed here since they are more suitable for revealing the three-dimensional large scale distribution. The first effort to obtain such a sample was carried out by the CfA (CfA1, Huchra et al. 1983) in the late 70's, in the northern hemisphere, measuring radial velocities for ≈ 2400 galaxies brighter than mag 14.5, in the galactic caps. This survey was the first to probe beyond the Virgo Supercluster, showing that galaxies are distributed preferentially in relatively thin and interconnected structures, delineating large empty regions and has been largely used to confront numerical N-body simulations. The results from this survey stand as fundamental contributions to the understanding of the large scale distribution of luminous matter, enabling the determination, with a large and homogeneous sample, of important parameters such as the galaxy mean density, luminosity function, different peculiar velocity statistics and estimates of the cosmological parameter (Davis et al. 1982, Davis and Huchra 1982, Davis and Pebbles 1983). However, there are some points that remain unanswered. For instance, to what extent do the peculiar motions induced by the Virgo Supercluster, which dominates the sample volume, influence the results. Also, the largest structures observed have dimensions of the order of the survey depth, casting some doubts if this sample could be taken as a fair representation of the Universe.

The need for improving this database led us to carry out the Southern Sky Redshift Survey (SSRS, da Costa et al. 1988) in a comparable area of the sky, in the direction opposite to Virgo, in the southern galactic cap. This effort was performed by a group of astronomers of the Observatório Nacional (O.N.), CfA, University of California and South African Astronomical Observatory, observing about 2000 galaxies selected from the ESO/Uppsala catalog (Lauberts, 1982). The different selection criterion (diameter) implied in a higher percentage of late type and low surface brightness galaxies as compared to the CfA1 sample. Other areas in the southern hemisphere were also surveyed in order to complete both the northern and southern galactic caps below $|b| = 30°$ and the resulting sample (CfA1 plus Southern Survey) in these caps comprise ≈ 5600 galaxies brighter than mag 14.5, 90% complete in radial velocity determinations. Figure 1 shows the projected galaxy distribution of these surveys onto galactic coordinates. Although an "effective" depth ≈ $60h^{-1}$ Mpc (H_0 = 100h km/s/Mpc) is derived from completeness arguments, it is possible to detect structures as large as $100h^{-1}$ Mpc due to the large angular coverage of these surveys.

The analyses of the Southern Survey data (Pellegrini et al 1989, Maia 1989, Maia et al. 1989, Pellegrini et al. 1990a,b, Pellegrini and da Costa 1990, Maia and da Costa 1990a,b, Santiago and da Costa 1990) revealed that:

1 - The mean galaxy density derived within an area 1.7 times that of the CfA1 is about $8x10^{-3}$ galaxies (brighter than M = -18.5) / Mpc^{-3}, smaller than the northern value (≈$12x10^{-3}$). The density estimator used, which is not affected by the inhomogeneities of the samples, is more stable when derived for the southern sample, which favours the lower value.

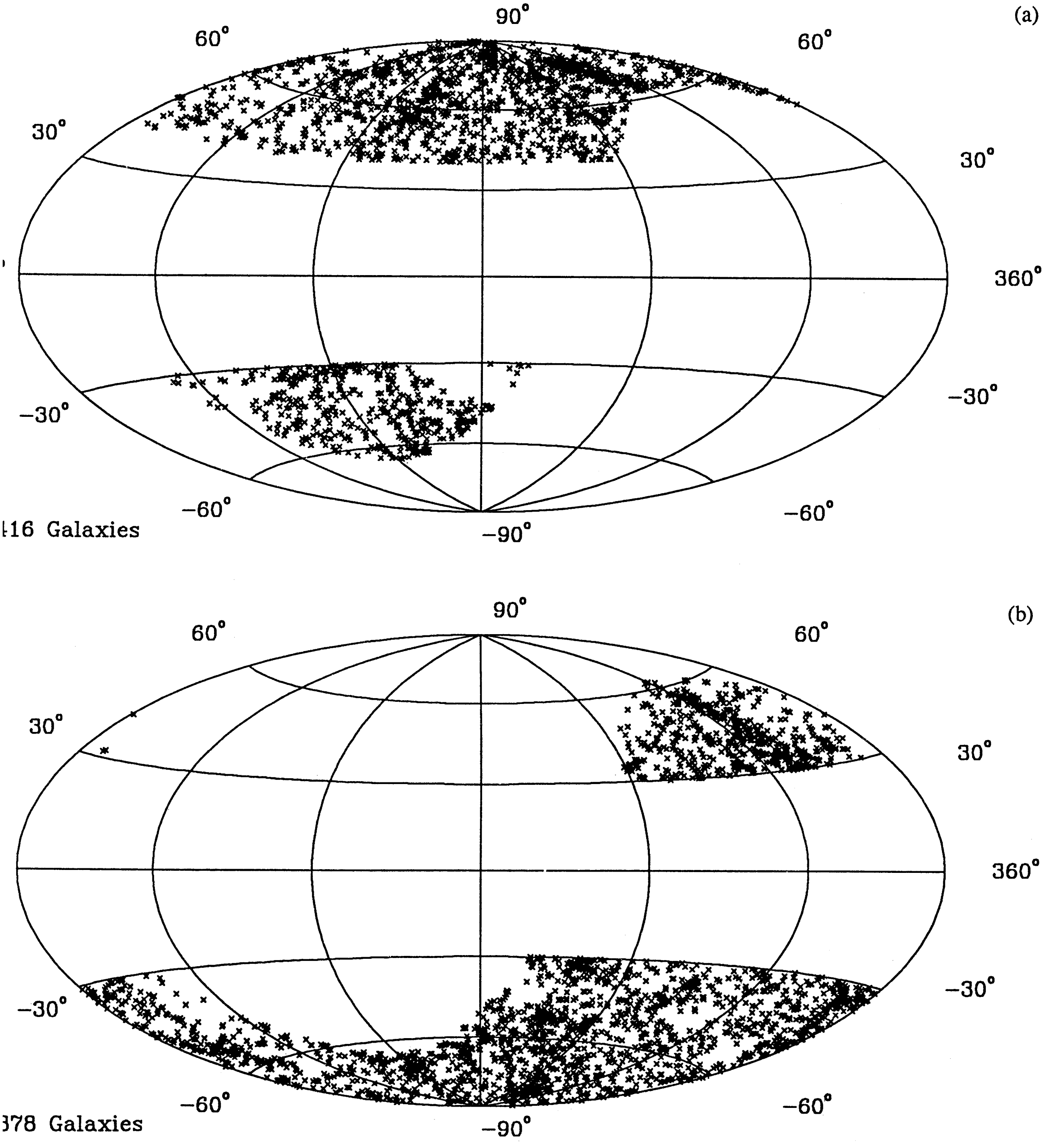

Figure 1. Aitoff equal-area projections, in galactic coordinates, of the CfA1 (a) and Southern (b) samples. The CfA sample covers 1.85 steradians in the northern galactic cap (b ≥ 40°, δ ≥ 0°) and 0.83 steradians in the southern galactic cap (b ≤ -30°, δ ≥ -2.5°) and includes 2416 galaxies brighter than mag 14.5. The most prominent structures are: Virgo (l=286°, b=74°), Coma (near northern galactic pole), Ursa Major (l=141°, b=57°) and part of the Perseus-Pisces filament (l=118°, b=-32°). The Southern sample covers 2.3 steradians in the southern cap (b ≤ -30°, δ ≤ -2.5) and 0.75 steradians in northern cap (b ≥ 30°) down to approximately the same magnitude limit, including 3200 galaxies. Most prominent structures are: Eridanus (l=214°, b=-52°), Fornax (l=236°, b=-54°), and part of the Telescopium-Pavo-Indus cloud (l=356°, b=-42°).

2 - Rich clusters such as Virgo and Coma are not present in the southern sample. The most noticable systems are the nearby Eridanus and the Fornax clusters. This fact allows a better view of the large scale structures, due to the absence of significant virial motions which introduce distortions in redshift maps, as shown in figure 2 where we present two slices of 15° in declination taken from the southern data. However, this difference may be a first indication that the sampled volume is not sufficiently large. Since the Southern Survey is not significantly deeper than the CfA1, the largest structures are also of the order of the survey depth.

3 - At larger scales, galaxies seem to be distributed on "walls" of sizes up to $80h^{-1}$ Mpc and thickness not exceeding $10h^{-1}$ Mpc, without apparent curvature, that intercept each other forming an interconnected network suggestive of a sponge-like topology (Gott et al. 1986). These coherent structures are easily seen in figure 2. There are, also, less prominent, sometimes curved filaments, linked to these "walls". The whole distribution is connected at a density contrast $\rho/\rho_m \approx 4$ (where ρ_m is the sample mean density) and altogether occupies less than 20% of the total volume. The large scale distribution is reasonably well represented by the results of N-body simulations of both hot (e.g. Shapiro et al. 1983) and cold (Davis et al. 1985) dark matter, altough there are problems with the time scale for galaxy formation in the former and a biasing mechanism (e.g. Dekel 1987) is required in the latter so that galaxies form preferentially is regions of higher density.

4 - If voids are defined as the rest 80% of the volume they are completely interconnected, permeating the whole surveyed region. Even if they are defined, in a restrictive manner, as regions with a density contrast below $\rho/\rho_m = 0.25$, they form only one structure, occupying 60% of the total volume. There is no evidence in this southern sample, of an empty region completely surrounded by galaxies as in a bubble-like topology suggested by de Lapparent et al. (1986). Large empty regions as those seen in figure 2, are easily produced in simulations of hot dark matter, but are really completely devoid of galaxies. In the cold dark matter scenario, galaxies are expected to exist in voids which are, only, very low density regions.

5 - Groups of galaxies were identified as structures defined by a density contrast $\rho/\rho_m = 20$, applying an identification procedure similar to that used by Geller and Huchra (1983). About 90 groups with more than two galaxies are identified to 8000 km/s, yielding a projected density surface of 50 groups/steradians, smaller than that of the CfA1 (66 groups/steradians). These groups delineate the overall large scale structure and are not found preferentially close to the interception of the "walls", as the rich Coma cluster in the north. Preliminary results indicate that: galaxies with active nuclei seem to be more frequently found in groups, suggesting that nuclear activity may be associated to environmental effects; groups in denser regions show, in the mean, a tendence to have a larger number of member galaxies, what could be either a consequence of biased galaxy formation or a signal of cluster formation by merging groups .

6 - Surface brightness seems to be closely associated with the correlation properties of galaxies. Determinations of central surface brightnesses (CSB) made at Observatório Nacional for galaxies contained in the diameter-limited SSRS sample (which covers a large range of surface brightness, including many late spirals, irregulars and dwarfs) indicate that the high-CSB galaxies are more clustered than the low-CSB galaxies, even within a given morphological type, an observational result expected in a biased cold dark matter scenario (e.g. Blumenthal et al. 1984).

7 - The acceleration induced on the Local Group by the galaxy distribution within the galactic caps $|b| \geq 30°$ is basically produced within a distance of $\approx 50h^{-1}$ Mpc. The peculiar motion of the Local Group, as derived from the dipole pattern of microwave background radiation (Lubin et al. 1983), cannot be accounted for by this distribution. A significant component in a direction close to the galactic plane is necessary to explain this motion, as suggested by various authors. The distribution of galaxies within $50h^{-1}$ Mpc and hidden by Galactic obscuration seems to play an important role in determining this motion (e.g. Faber and Burstein 1988).

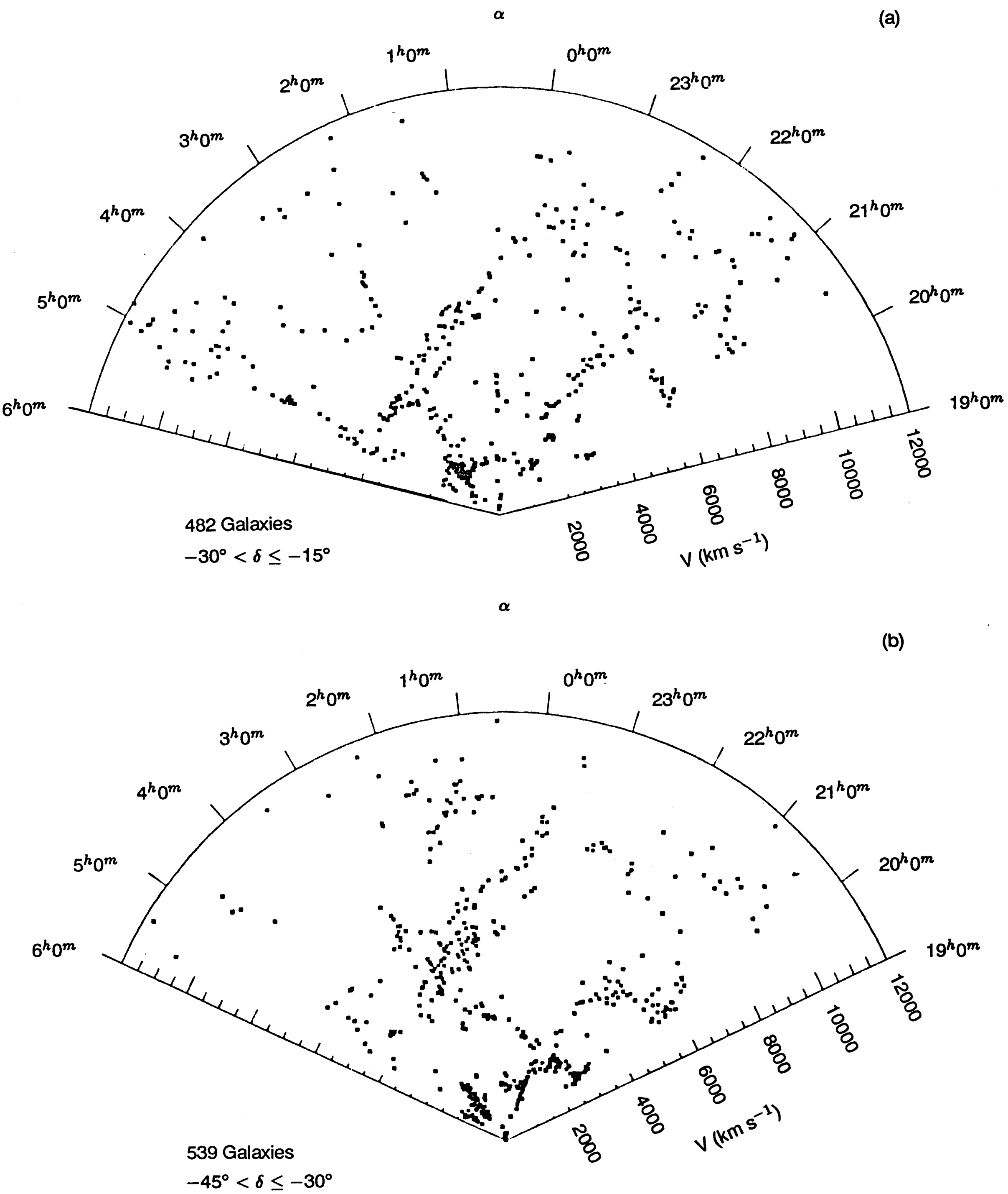

Figure 2. Radial velocity versus right ascension plots showing the slices (a) $-30° \leq \delta \leq -15°$ and (b) $-45° \leq \delta \leq -30°$. Since the slices are adjacent, the coherence of most structures in both plots shows that they are "walls". That stretching from (5^h, 4000 km/s) to (0^h, 10000 km/s) extends northward and southward. The largest coherence scale seen in these plots is $\approx 60h^{-1}$ to $80h^{-1}$ Mpc. Note the high degree of connectivity of the overall distribution. Significant virial motions can only be seen for the Eridanus cluster in panel (a) at (3.6^h, 1500 km/s) and the Fornax cluster in panel (b) at (3.6^h, 1500 km/s). The large empty region seen in panel (b) centered on (23^h, 6000 km/s), the Sculptor void, is specially interesting since its closer portion can be promptly examined by deeper surveys.

THE FAIR SAMPLE PROBLEM

The question if we have already obtained a fair sample of the Universe with the database of the CfA1 and the SSRS can be approached by verifying the reproducibility of the clustering properties of these two independent samples. For this analysis it is necessary to define statistical subsamples obtained by volume-limiting the data, i.e., considering only galaxies closer than a given distance and brighter than the absolute magnitude corresponding to the apparent magnitude limit of the sample at that distance (Pellegrini et al. 1990b). One of the most used clustering statistics is the two-point spatial correlation function $\xi(r)$ (e.g. Peebles 1980) which is related to the primordial perturbation spectrum and measures the excess probability, over a random sample, of finding a pair of galaxies separated by a given distance. The resulting functions calculated for the subsamples of the northern and southern data volume-limited at 4000 and 6000 km/s, (figures 3a and 3d, respectively) are very similar, indicating identical clustering properties, in spite of the different selection criteria of the CfA1 and SSRS. However, due to the shallowness of these subsamples, this statistic does not yield reliable results for scales greater than $10h^{-1}$ Mpc, since the large scale inhomogeneities of the samples (which have dimensions of the order of the volume surveyed) introduce uncertainties at these scales. Moreover, different corrections for peculiar motions (e.g. Virgo infall models) which are uncertain, also modify significantly the results.

Thus, in addition of the correlation function, it is useful to apply other clustering statistics suitable for larger scales, such as: a)- the percolation analysis (Einasto et al. 1984), which investigates the topology of the galaxy distribution, by measuring the "growth" of the largest system defined by increasing neighbor radii (or decreasing densities) and b)- the nearest-neighbor distance distribution (Ryden and Turner 1984), which determines a characteristic linear dimension of the voids through a histogram of distances of galaxies to the nearest point of a grid superposed on the sample volume. Figures 3b and 3c, which present the results of the percolation analysis and the nearest neighbor distribution for subsamples of the CfA1 and SSRS volume-limited at 4000 km/s, show the similarity of the clustering properties of these subsamples. At larger scales the same conclusion can be inferred from the subsamples volume-limited at 8000 km/s, not shown here. However, there is a significant difference between the samples volume-limited at 6000 km/s, where the SSRS data show slower percolation (figure 3e) and larger voids (figure 3f). Careful examination of the radial velocity versus right ascension plots shows that this is due to the greater relative prominence of a large empty region in the south (the void in Sculptor) whose "center" is at about 6000 km/s.

This result indicates that sampling effects are present in this comparison; a survey volume $\approx 60h^{-1}$ Mpc in depth placed on different locations (northern and southern caps) has different statistical properties. On the other hand, it may be an indication of the existence of a characteristic scale in the galaxy distribution; typical dimensions of the "walls" of galaxies and empty regions are about $60h^{-1}$ Mpc as mentioned before. If, for instance, we assume a toy model in which galaxies are distributed on a network of surfaces defining cells with this typical size, a sampling volume with this dimension centered on an interception of surfaces will yield different clustering properties from one centered on an empty region. However, it is clearly premature to draw definite conclusions based on these samples. If there is a characteristic scale in the galaxy distribution an adequate sampling should have an "effective" depth of, at least, twice this scale.

Moreover, the overall results presented above show that it is not possible with the CfA1 and SSRS databases to evaluate conclusively the correct scenario for galaxy formation. Indeed, a scenario with a coherence length, such as that assuming hot dark matter, reproduces reasonably well the large scale structure but faces difficulties in many aspects concerning galaxy formation and its time scale; even the cell-like coherent structures naturally formed in the simulations, last only for a very short time (White 1988). The cold dark matter scenario with the addition of a biasing mechanism, seems able to explain, not only galaxy properties, but also many clustering properties at small, medium and moderatly large scales (White et al. 1987); the Universe as a whole could have $\Omega = 1$, as expected from inflation (Guth 1981) and the luminous matter $\Omega \approx 0.2$ as inferred from dynamical estimates. On the other hand, large-scale coherent flows such as those reported by Dressler et al. (1987), partaken by a region with dimension $\approx 60h^{-1}$ Mpc, containing the Local Group, is not expected in this model. In addition, the volume-limited subsamples used to confront these models do not contain galaxies

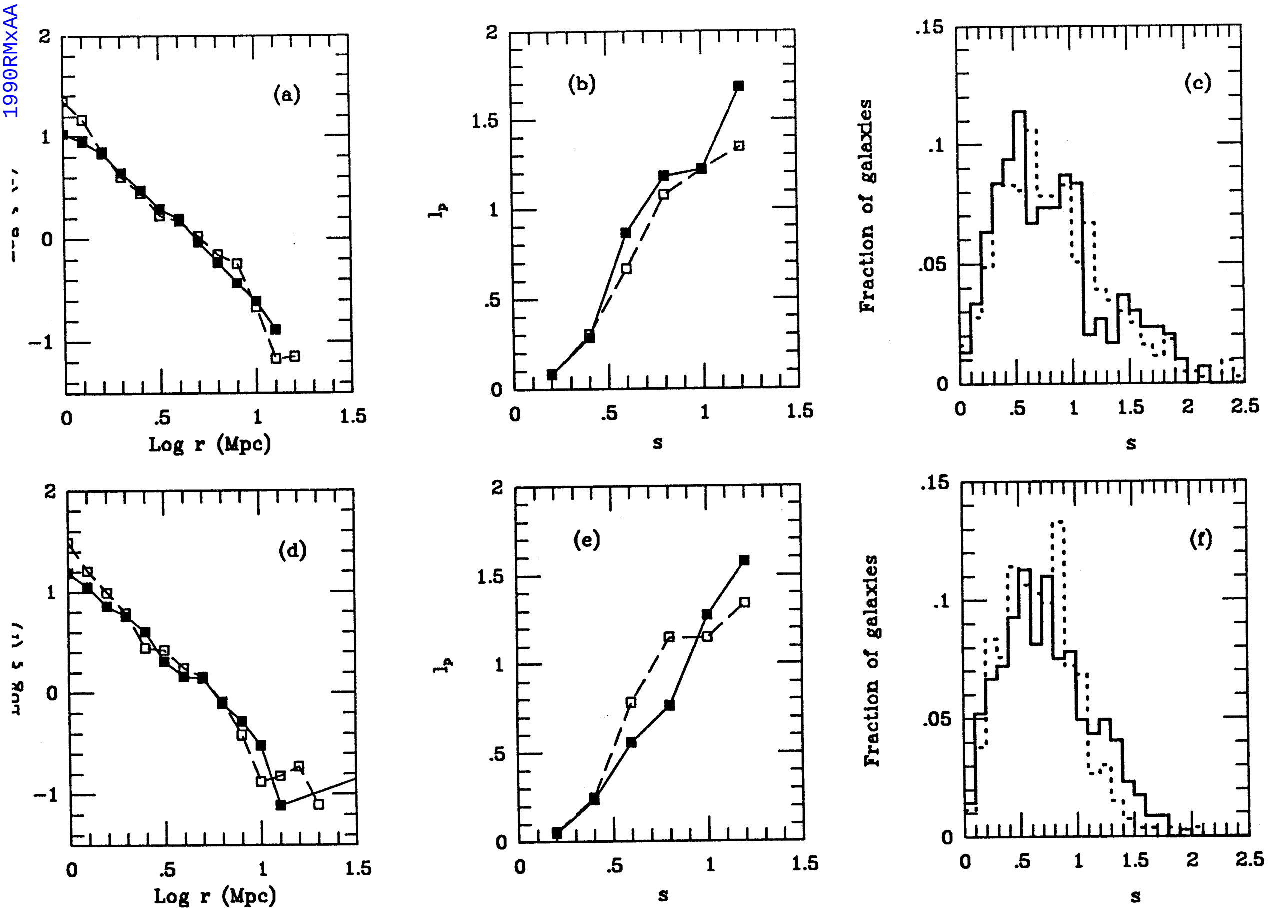

Figure 3. Correlation function (a,d), percolation parameter (b,e) and histogram of nearest neighbor galaxy (c,f) for the subsamples of the SSRS (continuous line, filled symbols) and the CfA1 (dashed lines, empty symbols), volume limited at 4000 km/s (upper panels) and 6000 km/s (lower panels). The correlation function was estimated comparing the number DD of galaxy pairs with internal separation r in each subsample with the number DR of pairs (with the same internal separation) formed by a galaxy and a point of a random sample generated over the subsample volume. The estimator shown in this figure is $\xi(r) = (DD/DR)(n_r/n_g) - 1$, where n_r and n_g are the average densities of the real and random distributions. The percolation parameter is defined as $l_p = l_{max}/L$, where l_{max} is the maximum dimension of the largest system formed by galaxies closer than r to each other and L is a characteristic linear dimension of the total volume of the subsamples. This parameter is shown as a function of the normalized radius $s=r/r_0$, where r_0 is the mean interparticle distance of each subsample. The nearest neighbor distribution is shown as the fraction of galaxies whose minimum distance to a point of a grid superposed on the subsample volume is r. This distribution is also shown as a function of a normalized distance $s=r/r_0$.

intrinsically fainter than a limit imposed by the apparent limiting magnitude of the survey (e.g. M = -18.5 for subsamples volume-limited at 4000 km/s). In fact, Geller and Huchra (1988) claim that surveys to fainter limiting magnitudes will turn up galaxies in the voids, although proportionately more in the structures already seen. Thus, the definition of a fainter sample could bring insight to this debate and remains as an important task to be done.

THE EXTENSIONS, PRELIMINARY RESULTS AND PROSPECTS

For this reason both the CfA and the O.N. began the extensions of their previous surveys to deeper limits, obtaining radial velocities for galaxies down to mag ≈ 15.5, in declination strips. The total area already completed by the CfA includes 6 slices of ≈ 6°x130° in the northern hemisphere (Geller and Huchra 1988). The O.N. group (with A. Fairall and D. Latham) has almost completed a slice 10°X120° centered on declination -35° (da Costa et al. 1989), a region containing the large void in Sculptor. This southern extension is, nowadays, a collaboration project of the O.N with the CfA, S.A.A.O. and Universidade Nacional de Cordoba and the observations are being made at CASLEO (Argentina) and S.A.A.O.. The advantage of surveying strips is that a complete and deep sample, is obtained in a reasonable time, enabling the investigation of clustering properties at larger scales. The CfA data show that typically 800 galaxies are found in each of these strips and the deeper magnitude limit implies an "effective" depth of ≈ $100h^{-1}$ Mpc. Although these surveys represent cuts in the galaxy distribution, hampering the complete three-dimensional view, Gott (1989) and collaborators have improved their analyses in order to investigate the topological properties of these "two-dimensional" surveys.

These extensions have shown that the wall of galaxies identified in the south may be even greater, extending to at least $150h^{-1}$ Mpc (da Costa et al. 1989), while in the north Geller and Huchra (1989) reported the existence of another great wall as large as this. Figure 4 is a composition of two slices of ≈ 10° in the southern and northern data, centered respectively on -35° and +35°, where these two very large structures are seen. Although this figure does not represent, in fact, a cut through the 3-d distribution it is useful to show an approximate view of the overall distribution and its north-south prolongation. These great walls are probably not single structures but seem to be formed by connected structures of smaller sizes (about $60h^{-1}$ Mpc ?). However, this question remains to be proved when the full three-dimensional distribution is obtained. Another important (although partial) result is that in the slices so far surveyed, the fainter sample did not include galaxies in some of the previously known empty regions. The few galaxies included in previous voids seem to belong to thin structures (filaments or walls) crossing them. In order to detect a possible evidence for biasing in the process of galaxy formation, L. da Costa, R. Giovanelli and M. Haynes initiated a program to determine radial velocities from HI measurements of dwarf and very low surface brightness galaxies, belonging to the SSRS sample, but impossible to get an optical redshift. An observational evidence for existence of galaxies in voids is, per se, an important point in favour of the cold dark matter scenario. If these galaxies are low surface brightness objects, a biasing mechanism should have been relevant in galaxy formation. Other projects under way are related to the large-scale flows (e.g. Lynden-Bell et al 1988) and their importance to provide challenges to galaxy formation scenarios. The possibility of using all the spectroscopic information available from the databases to derive distance indicators is being investigated and if reliable, could help, together with photometric measurements, in establishing limits on large scale flows throughout the observed distribution. These flows are specially interesting if detected in the large walls, since the different scenarios of galaxy formation predict different observational results: the flows are significant in the "pancake" scenario but negligible in the hierarchical model.

FINAL REMARKS

Finally, it should be mentioned that the surveys described here cover about 50% of the celestial sphere, the rest being obscured by the galactic plane. Unfortunately, our Galaxy seems to hide a large concentration of galaxies, in the direction of Hydra-Centaurus. Surveys carried out by da Costa and collaborators (1986, 1987) in this region, emphasized the presence of a large agglomeration of galaxies around 4300 km/s, that later was shown to be part of the "Great Attractor" (Lynden-Bell et al. 1988), which is responsible for a large bulk motion in our surroundings. However, the deeper surveys are revealing that this structure may not be unique. As discussed by Geller and Huchra (1989), the great wall detected in the CfA extension, has also a mass comparable to that of the "Great Attractor". Moreover, these structures are not adequately mapped to allow the determination of their geometry and the discovery of large-scale flows introduces an additional complexity to their analysis (e.g.

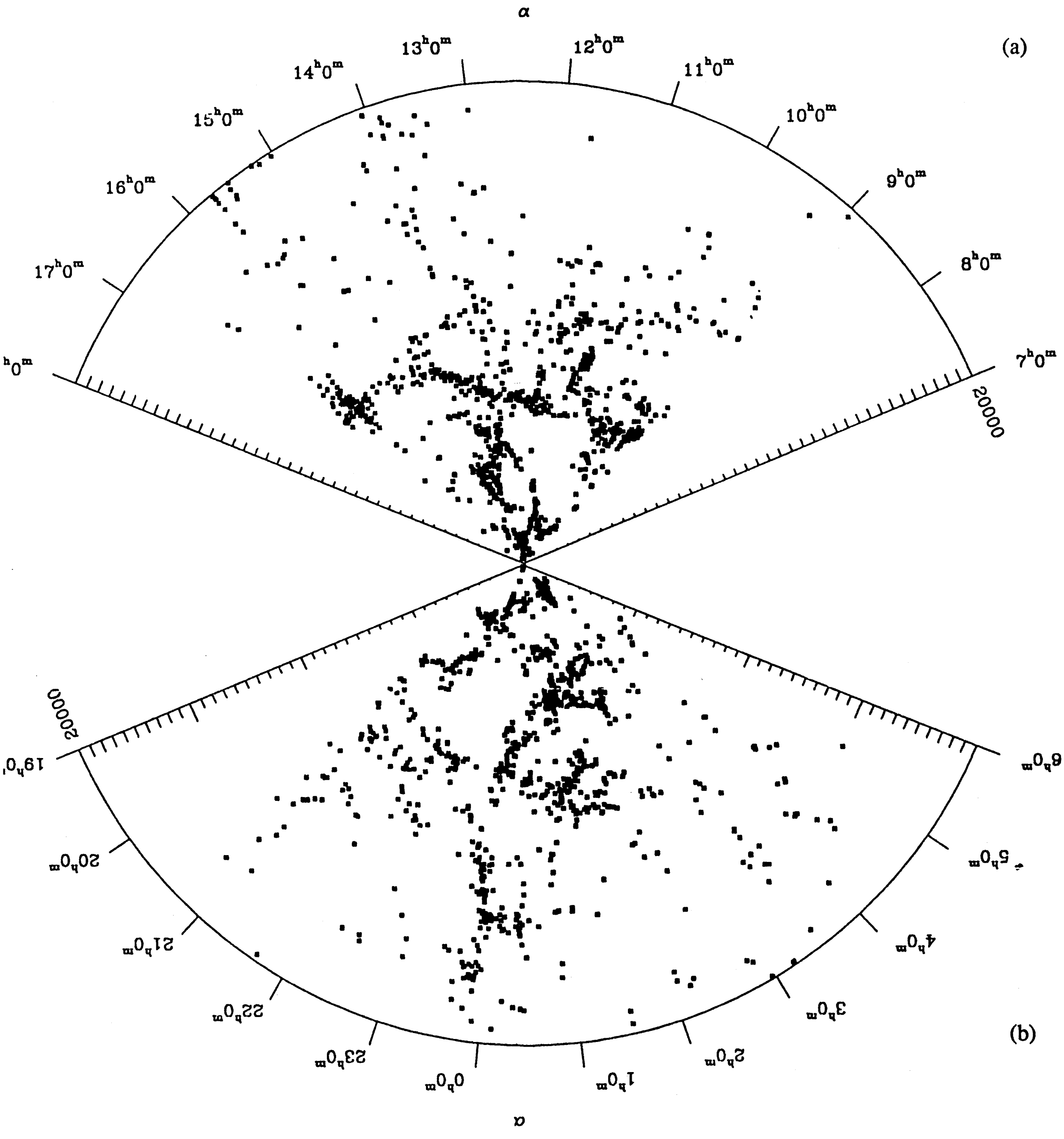

Figure 4. The southern slice -40°≤δ≤-30° (upper wedge) and its approximate continuation to the northern hemisphere 30°≤δ≤40° (lower wedge). The northern data were taken from ZCAT (Huchra 1989). This plot is not a planar cut through the distribution but a cut in a double cone shape. Note that the wall in the south seems to extend in a different direction to 18000 km/s. The wall in the northern slice spans all the right ascension range at ≈ 8000 km/s. However, coherence in a planar shape for both structures is mantained only within a scale ≈ 60h^{-1} Mpc. The void in Sculptor did not have galaxies added within its perimeter with the magnitude limit of the present extension.

Dressler 1988). All these points show that, although the biased cold dark matter scenario for the origin of galaxies and large structures seems to provide a good match to the galaxy distribution, neither it fully explains the observations, nor are the relevant questions posed by these observations, exhausted.

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. N. da Costa and P. S. Pellegrini: CNPq/Observatório Nacional, Rua General José Cristino 77, 20921, Rio de Janeiro, Brasil