THE LARGE-SCALE DISTRIBUTION OF GALAXIES AND WHAT IT TELLS US ABOUT COSMOLOGY

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The evolution of our knowledge of the large-scale distribution of galaxies in the Universe is reviewed. Since the early 1970's, when our knowledge of the galaxy distribution was primarily only two-dimensional, surveys of galaxy redshifts have significantly changed the view that the Universe is "sensibly uniform." Several recently completed large surveys of galaxies and galaxy clusters, most notably the CfA and Las Campanas Redshift Surveys, now provide excellent statistics to describe the topology of the galaxy distribution, including the galaxy-galaxy correlation function, pairwise velocity dispersion and the power spectrum. When compared to simulations of the growth of such structure based on a varitey of input physical parameters such as dominance by cold and hot dark matter, the data rule out many of the simplest models including neutrino and defect (strings, textures) dominated models and Standard CDM. Low Omega models, including those with a significant cosmological constant provide a better match, but still do not reproduce all of the features of the galaxy distribution.

1 Introduction

Like observational cosmology as we know it, the study of large-scale structure (LSS) in the Universe is a very young field. Before the 20th century, the prevailing world view was that the Universe was pretty small. Einstein, Lemaitre, Hubble and others, with their development of mathematical cosmology and their discovery of the expansion of the Universe and the vastness of cosmic distances set the stage for today's current debates on the values of various cosmological parameter and the correctness of cosmological models. The study of the large-scale distribution of matter in space, observational and theoretical, is both evidence used in the cosmological court and a beautiful subject in its own right. We know from the exquisite CMB data from COBE that the Universe started out pretty uniform and that currently it is very non-uniform, even on scales of several percent of the horizon radius.

1.1 The Dawn of Time (or of Extragalactic Astronomy...)

One of the many tasks Edwin Hubble set for himself was the determination of how uniform the Universe was at large distances. The theoretical prejudice then (and now) is that the Cosmological Principle holds – the Universe looks pretty much the same to any observer – which implies that, above some scale, it must be homogeneous and isotropic. In addition to his work on the expansion rate and the redshift distance relation, Hubble used the 100-inch Hooker reflector to obtain deep galaxy counts in different directions around the sky. This lead him to conclude that the Universe was "sensibly uniform." [1] Despite the "discovery" of clusters of galaxies by Zwicky and Shapley in the 1930's, most astronomers thought that clusters were rare and randomly distributed, and that the distribution of galaxies could be well described by a uniform "field." [2] This view held for nearly 30 years.

1.2 Evolution of the World View

Two events in the 1950's changed that. The realization by deVaucouleurs [3] that what is now called the Local Supercluster is a real dynamical entity, and the advent of the Palomar Sky Survey which brought with it the first major catalogs of clusters of galaxies [4] and of galaxies. [5, 6] These and other two-dimensional catalogs, [7] and the statistical analyses done on them by Peebles and his students [8] provided the first quantitative view of LSS. However, they only hinted at the the true 3-D complexity we see today.

1.3 Modern Redshift Surveys

The modern 3-D view of LSS started to be developed in the late 1970's. This was due primarily to the development of sensitive electronic detectors for both optical and radio wavelengths. They allowed large numbers of galaxy redshifts to be obtained in relatively short amounts of time. Small area surveys were performed by Chincarini and Rood, [9] and Tifft and Gregory [10] who found that the galaxy distribution was not uniform, and by Kirshner et al, [11] who discovered a very large void in the constellation Böotes. The first large-area coherent surveys were the RSA [12] and CfA1. [13] The former provided perhaps the best maps of the Local Supercluster, while the latter showed that the distribution of galaxies was most decidely not just clusters in a uniform field.

Since the early 1980's, there have been many redshift surveys. These include for example, 21-cm surveys of the Pisces-Perseus region [14], surveys of both IRAS Galaxies [15, 16] and optical galaxies[17] to determine the cause of our motion w.r.t. the CMB and to match the local density and velocity fields, surveys of Abell clusters, [19, 20] and various deeper surveys of selected regions and galaxy clusters. Recently two very large (15,000+ galaxies) surveys have been completed which provide exquisite information on the statistics and topology of galaxy clustering: the moderately deep Las Campanas Redshift

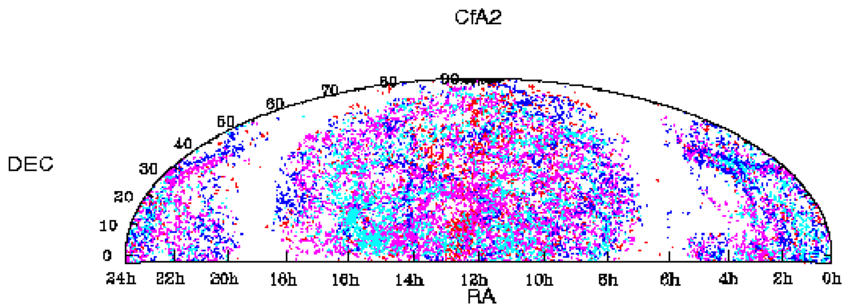

Figure 1: Extent of the CfA2 Survey. The plot shows the distribution on the sky of the 19038 galaxies brighter than B magnitude = 15.5.

Survey[21] with 25,000+ galaxies and the shallower but wider and contiguous second CfA survey[18, 22] with 18,000+ galaxies.

2 The Galaxy Distribution

Good examples of the 3-D galaxy distribution can be seen in the CfA Survey, which is wide area, uniform and densely sampled. Figure 1 shows the surface distribution of the galaxies in the sample. Figure 2 shows one radial velocity pie diagram, a cut in redshift space like an orange segment, between declinations 0° and 24° in the northern Galactic hemisphere. The many such cuts now available confirm the bubble-like nature of LSS discovered by de Lapparent, Geller and Huchra.[18] Voids are common, even endemic. Galaxies tend to be distributed on large surfaces, which are almost quiltlike in geometry, and clusters tend to lie in the surfaces and at interstices. The southern half of the Great Wall[23] can be seen running across Figure 2 at 8-11,000 km/s.

Between the two large optically selected galaxy surveys, LCRS and CfA, the general properties of the galaxy distribution are now fairly well defined. 90% of the volume of the Universe is in underdense regions or "voids." Void is a bit of a misnomer because they not empty, just underdense w.r.t. the mean by factors of 10-25. The surfaces occupy about 10% of the volume but contain $\sim$90% of the galaxies. The degree of definition, or "fuzziness" depends on morphological type and/or luminosity. Lower luminosity galaxies, which tend to be later morphological types, define the surfaces less well than bright

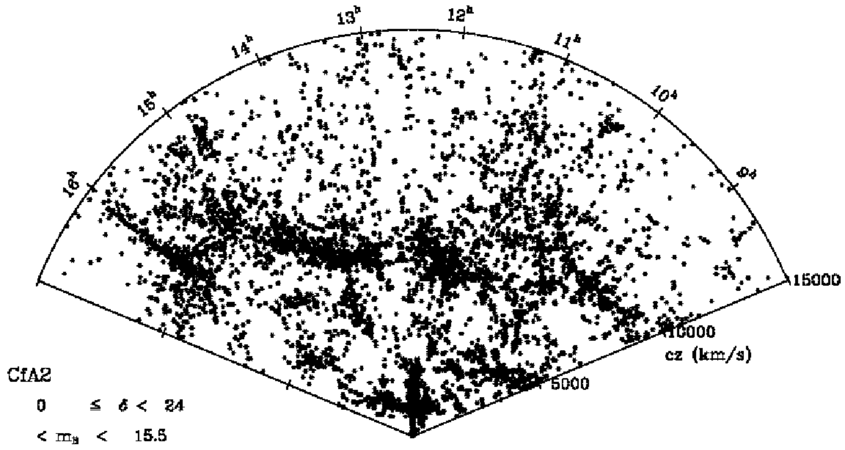

Figure 2: Thick slice of the CfA2 Survey in the north Galactic cap.

elliptical galaxies. Clusters are generally completely dominated by early type galaxies, while the inverse is true outside clusters.

2.1 Clustering Statistics

As noted above, quantitative information can be extracted from surveys of LSS in a variety of ways. The simplest statistics are counting statistics, e.g. counts of galaxies as a function of luminosity and/or morphological type. The best determination of the galaxy luminosity function as a function of morphological type is from the CfA surveys and is shown in Figure 3.[25] There is a good, rough theoretical description/prediction for the form of the global mass=luminosity function from Press and Schechter,[26] which has been expanded by many authors to include more detailed physics,[27] however there is as yet no complete theory of galaxy formation, especially including star formation, which can explain in detail Figure 3.

The next simplest statistics are the correlation functions, introduced by Totsuji and Kihara and by Peebles and coworkers in the early 1970's. Figure 4 shows the two-point or galaxy-galaxy correlation function, $\xi(s)$, measured for the CfA survey. These are excellent measures of the amplitude of clustering on small scales. Depending on the morphological type and luminosities of galaxies, the scale length of ξ for galaxies ranges from 5-8 h^{-1} Mpc. Surprisingly, the scale length for the clustering of clusters of galaxies is significantly larger.[28,29]

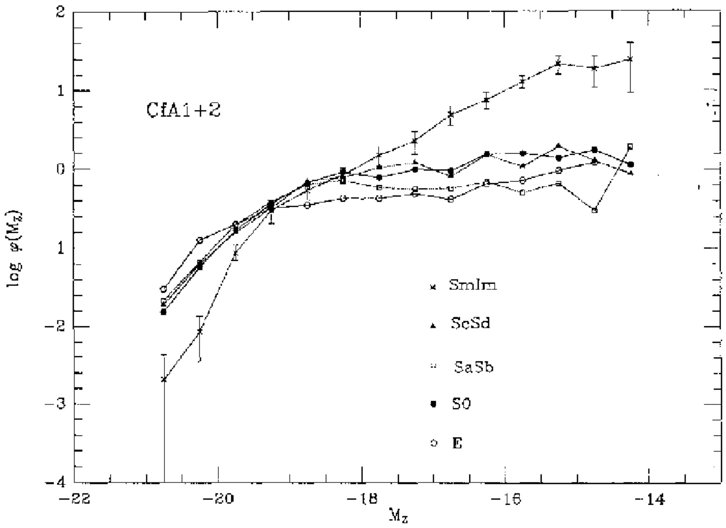

Figure 3: CfA2 Survey galaxy luminosity function for different morphological types. Note the similarity for all types but the latest spirals and irregulars, whose luminosity function rises steeply at the faint end.

The large amplitude of the clustering of clusters is one of the most difficult observations to match with the standard CDM model.

By definition, there are many other statistics, such as counts-in-cells, [30] the clustering power spectrum, velocity correlation functions and topological statistics like genus [31] which have been used to show that the galaxy distribution tends to be dominated by surfaces and not filaments and to test the Gaussian nature of the density fluctuations. [32,33] The topology of structures in the CfA survey is much more like intersecting surfaces than filaments. [30]

3 Beautiful Theories versus Ugly Experiment

When combined with simulations of the growth of structure in the Universe, observations of LSS become a powerful tool for determining cosmological parameters as well as the correctness of individual models. Currently the primary questions concern the value of the mean mass density of the Universe, Ω, what types of matter make up that density, and the existence or nonexistence of a Cosmological Constant, Λ. Simulations of the growth of structure in the Universe have been run by a large number of groups. [34,35,36,37] Simulations and data are then compared through statistics. For example, the early work of

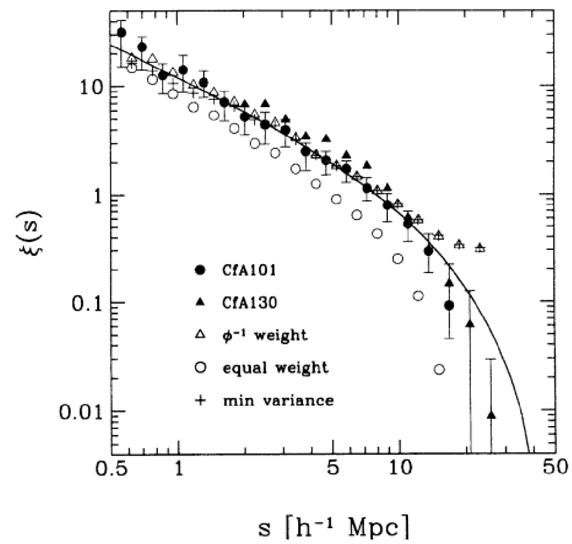

Figure 4: The galaxy-galaxy correlation function for subsamples of the CfA survey. The correlation length (where $\xi(s)$ drops to unity) is around 7.5 h^{-1} Mpc for this sample.

Davis et al. [34] effectively ruled out hot dark matter dominated models.

Two of the most powerful comparisons come from measures of the power of clustering on large scale and from the galaxy velocity field. The galaxy distribution shows a surprising amount of power on large scales. [38] Comparison of the power spectrum measured for the CfA survey and others with predictions of standard and open cold dark matter (SCDM, OCDM) models strongly favor lower Ω models. [24] If the model normalization is set at small scales, SCDM models predict too little power at large scale, and vice versa. OCDM or OCDM models with a Λ are favored. The observed power spectrum also strongly rules out models based on cosmic strings, textures and monopoles. [41]

Similarly, when compared with measures of the galaxy-galaxy pairwise velocity dispersion, [39] SCDM predicts dispersions that are too large, although the situation in this case is a little less clear. [40] When weighted by the number of pairs, and when rich galaxy clusters are included, the measured dispersion is actually close to predictions of Ω=1 models.

Other comparisons between data and simulations, such as the relative frequency of rich clusters, the cluster cluster correlation function and large-scale velocity fields also favor a low density Universe. Combined with mass determinations for galaxy systems via the Virial theorem, gravitational lensing and

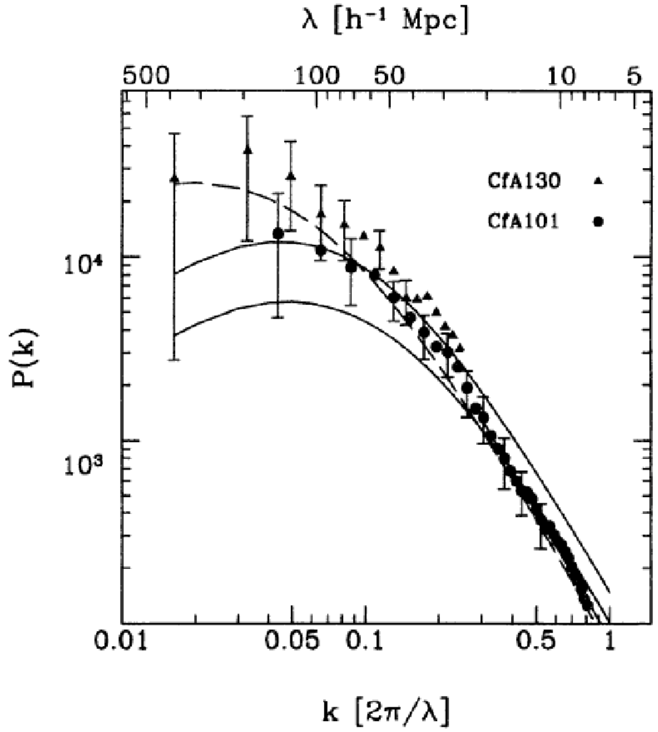

Figure 5: Redshift space power spectrum of subsamples of the CfA survey compared to predictions for three different cosmological models: SCDM ($\Omega h = 0.5$, lower solid curve), SCDM with a higher normalization (upper solid curve), and open CDM ($\Omega h = 0.2$, long-dashed curve). Models with a cosmological constant are similar to the OCDM model.

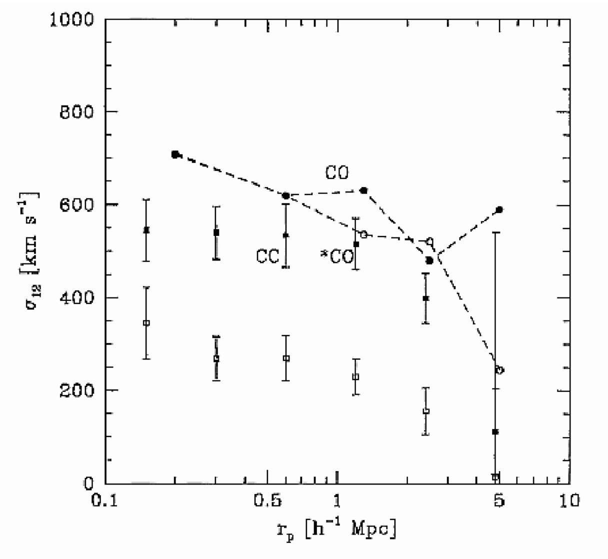

Figure 6: Measures of σ_{12}, the pairwise galaxy velocity dispersion versus scale length compared with simulations from Cen and Ostriker and from Couchman and Carlberg. The lower points are with rich clusters removed.

x-ray gas, and even Ω determinations from large-scale flows, the observational evidence now strongly favors $\Omega_M \sim 0.3$.

4 Conclusions

The galaxy distribution shows to much power on large scales (or small scales, depending on the normalization) compared to SCDM models. The observed velocity field also appears to be too quiet. SCDM and most other $\Omega = 1$ models are not good matches to the data, and models dominated by defects also fail. Low Ω CDM and mixed dark matter models are a better match to the data, although the topology seen in most simulations is filamentary while the observed distribution is more like a network of surfaces. So far, LSS has nothing definitive to say about Λ.

The not to distant future holds promise on both the observational and theoretical fronts. Simulations with greater dynamic range, so galaxies and LSS can be studied at the same time, and with more input physics, particularly hydrodynamics and magnetic fields are underway. We will have much better observational constraints on H_0 soon, infact the value seems to be converging somewhere in the vicinity of 65 km/s/Mpc.

Several new large galaxy redshift surveys are underway: 2DF of about 250,000 galaxies, 2MASS of 250,000, SDSS of 1,000,000 and LAMOST and the VLTIR, which are both aiming to observe 10^7 redshifts over the next decade. It will be fun!

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Additional information on the CfA survey and the CfA Catalogue of Galaxy Radial Velocities can be found at http://cfa-www.harvard.edu/~huchra.

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