Cosmological Tests from the New Surveys

Ofer Lahav
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

Abstract. We review cosmological inference from galaxy surveys at low and high redshifts, with emphasis on new Southern sky surveys. We focus on several issues: (i) The importance of understanding selection effects in catalogues and matching Northern and Southern surveys; (ii) The 2dF galaxy redshift survey of 250,000 galaxies (iii) The proposed 6dF redshift and peculiar velocity survey of near-infrared galaxies (iv) Radio sources and the X-Ray Background as useful probes of the density fluctuations on large scales, and (v) How to combine large scale structure and Cosmic Microwave Background measurements to estimate cosmological parameters. ¹

1 Introduction

It is believed by most cosmologists that on the very large scales the universe is an isotropic and homogeneous system. However, on scales much smaller than the horizon the distribution of luminous matter is clumpy. Galaxy surveys in the last decade have provided a major tool for cosmographical and cosmological studies. In particular, surveys such as CfA, SSRS, IRAS, APM and Las Campanas have yielded useful information on local structure and on the density parameter \( \Omega \) from redshift distortion and from comparison with the peculiar velocity field. Together with measurements of the Cosmic Microwave Background (CMB) radiation and gravitational lensing the redshift surveys provide major probes of the world’s geometry and the dark matter. In spite of the rapid progress there are two gaps in our current understanding of the density fluctuations as a function of scale: (i) It is still unclear how to relate the distributions of light and mass, in particular how to match the clustering of galaxies with the CMB fluctuations, (ii) Currently little is known about fluctuations on intermediate scales between these of local galaxy surveys (\( \sim 100h^{-1}\) Mpc) and the scales probed by COBE (\( \sim 1000h^{-1}\) Mpc).

Another unresolved issue is the value of the density parameter \( \Omega \). Putting together different cosmological observations, the derived values seem to be inconsistent with each other. Taking into account moderate biasing, the redshift and peculiar velocity data on large scales yield \( \Omega \approx 0.3 - 1.5 \), with a trend towards the popular value \( \sim 1 \) (e.g. Dekel 1994; Strauss & Willick 1995 for summary of results). On the other hand, the high fraction of baryons in clusters, combined with the baryon density from Big Big Nucleosynthesis suggests \( \Omega \approx 0.2 \) (White

¹ Invited talk, to appear in the Proceedings of the ESO/ATNF Workshop Looking Deep in the Southern Sky, 10-12 December 1997, Sydney, Australia, Eds. R. Morganti and W. Couch
et al. 1993). Moreover, an $\Omega = 1$ universe is also in conflict with a high value of the Hubble constant ($H_0 \approx 70 - 80$ km/sec/Mpc), as in this model the universe turns out to be younger than globular clusters. A way out of these problems was suggested by adding a positive cosmological constant, such that $\Omega + \lambda = 1$, to satisfy inflation. Two recent observations constrain $\lambda$: the observed frequency of lensed quasars is too small, yielding an upper limit $\lambda < 0.65$ (e.g. Kochanek 1996), and the magnitude-redshift relation for Supernovae type Ia (e.g. Perlmutter et al. 1998). The next decade will see several CMB experiments (e.g. Planck, MAP, VSA) which promise to determine (in a model-dependent way) the cosmological parameters to within a few percent. We shall focus here on several issues related to clustering and cosmological parameters from new surveys.

2 From ‘Biased Surveys’ to the ‘Real Universe’

Figure 1 shows a compilation of the current and future surveys, indicating for each survey its effective volume (in terms of its solid angle and median redshift) and the number of galaxies with measured redshift.

It is important to emphasize that each survey is selected by different criteria (e.g. wavelength and flux), hence any survey is biased! One should pay attention to the following aspects in analyzing surveys:

- Source Detection (e.g. 3-$\sigma$ selection, wavelet filtering, combining radio multi-components)
- Source Classification (e.g. star/galaxy separation - by eye or by Artificial Neural Networks) and multi-wavelength identification
- Incomplete Sky Coverage (e.g. the Zone of Avoidance)
- Matching Northern and Southern catalogues (e.g. the optical UGC/ESO, the radio 87GB/PMN)
- Poisson shot-noise, due to the finite number of galaxies
- Redshift distortion
- Biasing of particular tracer relative to the underlying mass distribution

3 New Surveys

Existing optical and IRAS redshift surveys contain 10,000-20,000 galaxies. The Parkes multi-beam survey in 21cm (HIPASS) will detect about 5,000 galaxies in the Southern hemisphere (see Stevelly-Smith in this volume). Another major step forward using multifibre technology will allow in the near future to produce redshift surveys of millions of galaxies. In particular, there are two major surveys on the horizon. The American-Japanese Sloan Digital Sky Survey (SDSS) will yield images in 5 colours for 50 million galaxies, and redshifts for about 1 million galaxies over a quarter of the sky (Gunn and Weinberg 1995). It will be carried out using a dedicated 2.5m telescope in New Mexico. The median redshift of the survey is $z \sim 0.1$. A complementary Anglo-Australian survey, the 2 degree Field (2dF), is described below (see also Boyle & Colless on both the galaxy and quasar 2dF surveys in this volume).
Fig. 1. The effective volume and number of galaxies of completed reshift surveys (solid circles) and surveys in preparation (crosses). The effective volume is defined here as $\omega R_{\text{med}}^3/3$, where $\omega$ is the solid angle of a survey, and $R_{\text{med}}$ its median comoving depth. Optically selected surveys include the Center for Astrophysics (CfA) survey, the Southern Sky Redshift Survey (SSRS), the Optical Redshift Survey (ORS), the ESO Slice Project (ESP), the Stromlo-APM (SAPM) and the Las Campanas Redshift Survey (LCRS), the 2-degree Field (2dF) galaxy survey, and the Sloan Digital Sky Survey (SDSS). The IRAS Point Source Catalogue (PSCZ) is selected in the infrared ($60\mu$), while 6dF/DENIS/2MASS is selected in the near infrared ($\sim 2\mu$). HIPASS is the Parkes multi-beam survey in 21 cm. (A compilation by S. Maddox and O. Lahav).
3.1 2dF

The 2dF galaxy survey will produce redshifts for 250,000 galaxies brighter than $b_J = 19.5^m$ (with median redshift of $z \sim 0.1$), selected from the APM catalogue. The survey will utilize a new 400-fibre system on the 4m AAT, covering $\sim 1,700$ sq deg of the sky. About 8,000 redshifts have been measured so far (March 1998). A deeper extension down to $R = 21$ for 10,000 galaxies is also planned for the 2dF survey.

- Accurate measurements of the power spectrum of galaxy clustering on scales $> 30h^{-1}$ Mpc allowing a direct comparison with CMB anisotropy measurements such as the recently approved NASA MAP and ESA Planck Surveyor satellites. The power-spectrum derived from the projected APM galaxies (see Figure 2) gives an idea about the scales probed by the 2dF redshift survey.
- Measurement of the distortion of the clustering pattern in redshift space providing constraints on the cosmological density parameter $\Omega$ and the spatial distribution of dark matter.
- Determination of variations in the spatial and velocity distributions of galaxies as a function of luminosity, spectral type and star-formation history, providing important constraints on models of galaxy formation.
- Investigations of the morphology of galaxy clustering and the statistical properties of the fluctuations, e.g. whether the initial fluctuations are Gaussian as predicted by inflationary models of the early universe.
- A study of clusters and groups of galaxies in the redshift survey, in particular the measurement of infall in clusters and dynamical estimates of cluster masses at large radii.
- Application of novel techniques (e.g. Principal Component Analysis and Artificial Neural Networks; Folkes, Lahav & Maddox 1996) to classify the uniform sample of 250,000 spectra obtained in the survey, thereby obtaining a comprehensive inventory of galaxy types as a function of spatial position within the survey.

For more details on the 2dF galaxy survey see [http://msowww.anu.edu.au/colless/2dF/](http://msowww.anu.edu.au/colless/2dF/)

3.2 6dF

It is has recently been proposed by the Anglo-Australian Observatory to automate the FLAIR multi-fibre facility at the 1.2m Schmidt telescope in Siding Spring Australia. The main purpose of the upgrading is to measure redshifts to $\sim 120,000$ galaxies principally selected in the Near InfraRed from the DENIS survey, and to measure internal motions (hence distance indicators and peculiar velocities) to $\sim 18,000$ galaxies. The unique feature of this survey is the ability to probe mass on both galactic and cosmological scales.

The European DENIS project (DEep Near-Infrared Southern Sky Survey) has begun in 1995 to image the entire Southern sky in three bands in the Near Infrared.
InfraRed (NIR): $I$(0.8 micron), $J$(1.25 micron) and $K_s$ (2.15 micron). NIR light from galaxies is dominated by the old stellar population, hence is more directly related to the underlying mass than surveys in the optical or far-infrared. Moreover, the NIR light is little affected by Galactic extinction, making it ideal to probe galaxies through the Zone of Avoidance. Another large survey at 2 microns (2MASS) is carried out by a US team. In the case of DENIS the main purpose of the survey is to measure redshift to 90,000 NIR-selected galaxies brighter than $J = 13.7$ (with median redshift $\bar{z} \approx 0.04$) plus perhaps 30,000 additional galaxies over 18000 deg$^2$ in about 160 spectroscopic nights. Even more exciting than this big redshift survey is the possibility to measure velocity dispersions for elliptical galaxies and rotation velocities for spiral galaxies. This will produce a uniform set of $\sim$ 18000 galaxies with distance indicators (via the Tully-Fisher relation), and hence peculiar velocities. Currently the most recent sample of peculiar velocities (Mark III) includes only $\sim$ 3000 galaxies taken from various subsets. The combination of the redshift and peculiar velocity surveys over an entire hemisphere will allow us to reconstruct maps of NIR galaxy and mass distributions, e.g. by the Potent (Dekel 1994) and Wiener (e.g. Webster et al. 1997) methods, to estimate the density parameter $\Omega$ and to characterize biasing. Assuming that it will take 2 years to build 6dF, the entire redshift survey can be finished by 2001 and the peculiar velocity survey by 2003. Detailed proposals can be found on http://msowww.anu.edu.au/colless/6dF/

4 Probes at High Redshift

The big new surveys (SDSS, 2dF) will only probe a median redshift $\bar{z} \sim 0.1$. It is still crucial to probe the density fluctuations at higher $z$, and to fill in the gap between scales probed by previous local galaxy surveys and the scales probed by COBE and other CMB experiments. Here we discuss the X-ray Background (XRB) and radio sources as probes of the density fluctuations at median redshift $\bar{z} \sim 1$. Other possible high-redshift traces are quasars and clusters of galaxies.

4.1 Radio Sources

Radio sources in surveys have typical median redshift $\bar{z} \sim 1$, and hence are useful probes of clustering at high redshift. Unfortunately, it is difficult to obtain distance information from these surveys: the radio luminosity function is very broad, and it is difficult to measure optical redshifts of distant radio sources. Earlier studies claimed that the distribution of radio sources supports the 'Cosmological Principle'. However, the redshift distribution of radio sources is now better understood, and it is clear that the wide range in intrinsic luminosities of radio sources would dilute any clustering when projected on the sky. In fact, recent analyses of new deep radio surveys (e.g. FIRST) suggest that radio sources are indeed clustered at least as strongly as local optical galaxies (e.g. Cress et
Nevertheless, on the very large scales the distribution of radio sources seems nearly isotropic. Comparison of the measured quadrupole in a radio sample in the Green Bank and Parkes-MIT-NRAO 4.85 GHz surveys to the theoretically predicted ones (Baleisis et al. 1998) offers a crude estimate of the fluctuations on scales $\lambda \sim 600 h^{-1} \text{Mpc}$. The derived amplitudes are shown in Figure 2 for the two assumed Cold Dark Matter (CDM) models. Given the problems of catalogue matching and shot-noise, these points should be interpreted at best as ‘upper limits’, not as detections. A new Southern radio survey, SUMSS, is described by Sadler in this volume.

### 4.2 XRB

Although discovered in 1962, the origin of the X-ray Background (XRB) is still unknown, but is likely to be due to sources at high redshift (for review see Boldt 1987; Fabian & Barcons 1992). Here we shall not attempt to speculate on the nature of the XRB sources. Instead, we utilise the XRB as a probe of the density fluctuations at high redshift. The XRB sources are probably located at redshift $z < 5$, making them convenient tracers of the mass distribution on scales intermediate between those in the CMB as probed by COBE, and those probed by optical and IRAS redshift surveys (see Figure 2).

The interpretation of the results depends somewhat on the nature of the X-ray sources and their evolution. The rms dipole and higher moments of spherical harmonics can be predicted (Lahav et al. 1997) in the framework of growth of structure by gravitational instability from initial density fluctuations. By comparing the predicted multipoles to those observed by HEAO1 (Treyer et al. 1998) it is possible to estimate the amplitude of fluctuations for an assumed shape of the density fluctuations (e.g. CDM model). Figure 2 shows the amplitude of fluctuations derived at the effective scale $\lambda \sim 600 h^{-1} \text{Mpc}$ probed by the XRB. One can use this estimate to derive the fractal dimension $D_2$ of the universe on large scales. Although the fractal dimension of the galaxy distribution on scales $< 20 h^{-1} \text{Mpc}$ is $D_2 \approx 1.2 \ldots 2.2$, the fluctuations in the X-ray Background and in the Cosmic Microwave Background are consistent with $D_2 = 3$ to within $10^{-4}$ on the very large scales (Wu et al. 1998).

### 5 Joint Parameter Estimation LSS/CMB

Observations of anisotropies in the Cosmic Microwave Background (CMB) provide one of the key constraints on cosmological models and a significant quantity of experimental data already exists (e.g. Gawiser & Silk 1998 and Lineweaver in this volume).

Galaxy redshift surveys, mapping large scale structure (LSS), provide another cosmologically important set of observations. The clustering of galaxies in redshift-space is systematically different from that in real-space (Kaiser 1987, Hamilton 1997 for review). The mapping between the two is a function of the
Fig. 2. A compilation of density fluctuations on different scales from various observations: a galaxy survey, deep radio surveys, the X-ray Background and Cosmic Microwave Background experiments. The measurements are compared with two popular Cold Dark Matter models. The Figure shows mean-square density fluctuations \((\Delta \rho)^2 \propto k^3 P(k)\), where \(k = 1/\lambda\) is the wavenumber and \(P(k)\) is the power-spectrum of fluctuations. The solid and dashed lines correspond to the standard Cold Dark Matter power-spectrum (with shape parameter \(\Gamma = 0.5\)) and a 'low-density' CDM power-spectrum (with \(\Gamma = 0.2\)), respectively. Both models are normalized such that the rms mass fluctuation at \(8h^{-1}\) Mpc spheres is \(\sigma_8 = 1\) (at \(k \sim 0.15\)). The open squares at small scales are estimates of the power-spectrum from 3D inversion of the angular APM galaxy catalogue (Baugh & Efstathiou 1994). The elongated 'boxes' at large scales represent the COBE 4-yr (on the right) and Tenerife (on the left) CMB measurements. The COBE 'box' corresponds to a quadrupole \(Q=18.0\, \mu K\) for a Harrison-Zeldovich mass power-spectrum, via the Sachs-Wolfe effect, or \(\sigma_8 = 1.4\) for a standard CDM model (Gawiser & Silk 1998). The solid triangles represent constraints from the distribution of radio sources brighter than 70 mJy from the PMN and 87GB samples. This quadrupole (Baleisis et al. 1998) probes fluctuations on scale \(\lambda^* \sim 600h^{-1}\) Mpc. The top and bottom solid triangles are upper limits of the amplitude of the power-spectrum at \(\lambda^*\), assuming CDM power-spectra with shape parameters \(\Gamma = 0.2\) and 0.5 respectively, and an Einstein-de Sitter universe. The crosses represent constraints from the XRB HEAO1 quadrupole (Lahav et al. 1997; Treyer et al. 1998). Assuming evolution, clustering and epoch-dependent biasing prescriptions, this XRB quadrupole measurement probes fluctuations on scale \(\lambda^* \sim 600h^{-1}\) Mpc, very similar to the scale probed by the radio sources. The top and bottom crosses are estimates of the amplitude of the power-spectrum at \(\lambda^*\), assuming CDM power-spectra with shape parameters \(\Gamma = 0.2\) and 0.5 respectively, and an Einstein-de Sitter universe. The fractional error on the XRB amplitudes (due to the shot-noise of the X-ray sources) is about 30%. (A compilation from Wu, Lahav & Rees 1998).
underlying mass distribution, in which the galaxies are not only mass tracers, but also velocity test particles. Estimates derived separately from each of the CMB and LSS data sets have problems with parameter degeneracy. Webster et al. (1998) combined results from a range of CMB experiments, with a likelihood analysis of the IRAS 1.2Jy survey, performed in spherical harmonics. Their method expresses the effects of the underlying mass distribution on both the CMB potential fluctuations and the IRAS redshift distortion. This breaks the degeneracy inherent in an isolated analysis of either data set, and places tight constraints on several cosmological parameters.

The family of CDM models analysed corresponds to a spatially-flat universe with an initially scale-invariant spectrum and a cosmological constant $\lambda$. Free parameters in the joint model are the mass density due to all matter ($\Omega$), Hubble's parameter ($h = H_0/100$ km/sec), IRAS light-to-mass bias ($b_{\text{iras}}$) and the variance in the mass density field measured in an $8h^{-1}$ Mpc radius sphere ($\sigma_8$). For fixed baryon density $\Omega_b = 0.0125/h^2$ the joint optimum lies at $\Omega = 1 - \lambda = 0.41 \pm 0.08$, $h = 0.46 \pm 0.06$, $\sigma_8 = 0.65 \pm 0.10$, $b_{\text{iras}} = 1.26 \pm 0.06$ (marginalised error bars correspond to 95 percent confidence). For these values of $\Omega$, $\lambda$ and $H_0$ the age of the universe is $\sim 18.7$ Gyr.

6 Discussion

We have shown some recent studies of galaxy surveys, and their cosmological implications. New measurements of galaxy clustering and background radiations can provide improved constraints on the isotropy and homogeneity of the Universe on large scales. In particular, the angular distribution of radio sources and the X-Ray Background probe density fluctuations on scales intermediate between those explored by galaxy surveys and CMB experiments. On scales larger than $300h^{-1}$ Mpc the distribution of both mass and luminous sources satisfies well the ‘Cosmological Principle’ of isotropy and homogeneity. Cosmological parameters such as $\Omega$ therefore have a well defined meaning. With the dramatic increase of data, we should soon be able to map the fluctuations with scale and epoch, and to analyze jointly LSS and CMB data.

Acknowledgments I thank my collaborators for their contribution to the work presented here. I also thank the conference organizers for the stimulating and enjoyable meeting, and acknowledge the hospitality of Tokyo University, where this paper was written.

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