Part 6. Large Scale Structure

LARGE SCALE STRUCTURE OF THE UNIVERSE

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Abstract. How is the universe organized on large scales? How did this structure evolve from the unknown initial conditions of a rather smooth early universe to the present time? The answers to these questions will shed light on the cosmology we live in, the amount, composition and distribution of matter in the universe, the initial spectrum of density fluctuations that gave rise to this structure, and the formation and evolution of galaxies, clusters of galaxies, and larger scale structures.

To address these fundamental questions, large and accurate sky surveys are needed—in various wavelengths and to various depths. In this presentation I review current observational studies of large scale structure, present the constraints these observations place on cosmological models and on the amount of dark matter in the universe, and highlight some of the main unsolved problems in the field of large-scale structure that could be solved over the next decade with the aid of current and future surveys. I briefly discuss some of these surveys, including the Sloan Digital Sky Survey that will provide a complete imaging and spectroscopic survey of the high-latitude northern sky, with redshifts for the brightest $\sim 10^6$ galaxies, 10^5 quasars, and $10^{3.5}$ rich clusters of galaxies. The potentialities of the SDSS survey, as well as of cross-wavelength surveys, for resolving some of the unsolved problems in large-scale structure and cosmology are discussed.

1. Introduction

Studies of the large-scale structure of the universe over the last decade, led by observations of the distribution of galaxies and of clusters of galaxies, have revealed spectacular results, greatly increasing our understanding of this subject. With major surveys currently underway, the next decade will provide new milestones in the study of large-scale structure. I will highlight

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what we currently know about large-scale structure, emphasizing some of the unsolved problems and what we can hope to learn in the next ten years from new sky surveys.

Why study large-scale structure? In addition to revealing the "skeleton" of our universe, detailed knowledge of the large-scale structure provides constraints on the formation and evolution of galaxies and larger structures, and on the cosmological model of our universe (including the mass density of the universe, the nature and amount of the dark matter, and the initial spectrum of fluctuations that gave rise to the structure seen today).

What have we learned so far, and what are the main unsolved problems in the field of large-scale structure? I discuss these questions in the sections that follow. I first list some of the most interesting unsolved problems on which progress is likely to be made in the next decade using upcoming sky surveys.

- Quantify the measures of large-scale structure. How large are the largest coherent structures? How strong is the clustering on large scales (*e.g.*, as quantified by the power spectrum and the correlation functions of galaxies and other systems)?
- What is the topology of large-scale structure? What are the shapes and morphologies of superclusters, voids, filaments, and their networks?
- How does large-scale structure depend on galaxy type, luminosity, surface brightness? How does the large-scale distribution of galaxies differ from that of other systems (*e.g.*, clusters, quasars)?
- What is the amplitude of the peculiar velocity field as a function of scale?
- What is the amount of mass and the distribution of mass on large scales?
- Does mass trace light on large scales? What is in the "voids?"
- What are the main properties of clusters of galaxies: their mass, mass-function, temperature-function, and dynamical state?
- What is the mass density, $\Omega_m \equiv \rho_m/\rho_{\rm crit}$, of the universe?
- How does the large-scale structure evolve with time?
- What are the implications of the observed large-scale structure for the cosmological model of our universe and for structure formation? (*e.g.*, What is the nature of the dark matter? Does structure form by gravitational instability? What is the initial spectrum of fluctuations that gave rise to the structure we see today? Were the fluctuations Gaussian?)

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2. Clustering and Large-Scale Structure

Two-dimensional surveys of the universe analyzed with correlation function statistics (Groth and Peebles 1977, Maddox *et al.* 1990) reveal structure to scales of at least $\sim 20h^{-1}$ Mpc. Large redshift surveys of the galaxy distribution reveal a considerably more detailed structure of superclusters, voids, and filament network extending to scales of ~ 50–$100h^{-1}$ Mpc (Gregory and Thompson 1978, Gregory *et al.* 1981, Chincarini *et al.* 1981, Giovanelli *et al.* 1986, de Lapparent *et al.* 1986, de Costa *et al.* 1988, Geller and Huchra 1989) The most recent and largest redshift survey, the Las Campanas Redshift Survey (Kirshner *et al.* 1996; see also Landy *et al.* 1996), with redshifts for $\sim 25 \times 10^3$ galaxies, is presented in Figure 1; it reveals the "cellular" nature of the large-scale galaxy distribution. The upcoming Sloan Digital Sky Survey (SDSS), expected to begin operation in 1997 (see §5), will provide a three dimensional map of the entire high-latitude northern sky to $z \sim 0.2$, with redshifts for approximately 10^6 galaxies. This survey, and others currently planned, will provide the large increase in the survey volume required to resolve some of the unsolved problems listed above. (See contribution by McKay, this volume, p. 49.)

The angular galaxy correlation function was first determined from the 2D Lick survey and inverted into a spatial correlation function by Groth & Peebles. They find $\xi_{gg}(r) \simeq 20r^{-1.8}$ for $r \lesssim 15h^{-1}$ Mpc, with correlations that drop to the level of the noise for larger scales. This observation implies

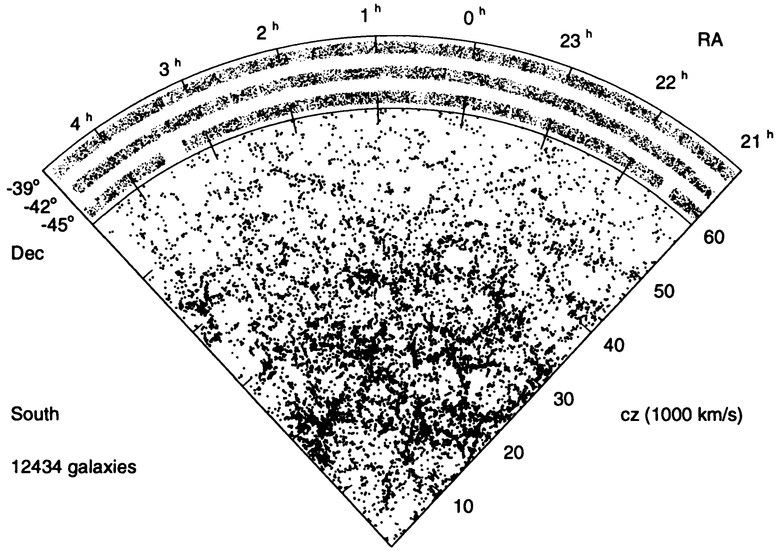

Figure 1. Redshift cone diagram for galaxies in the Las Campanas survey (Kirshner *et al.* 1996).

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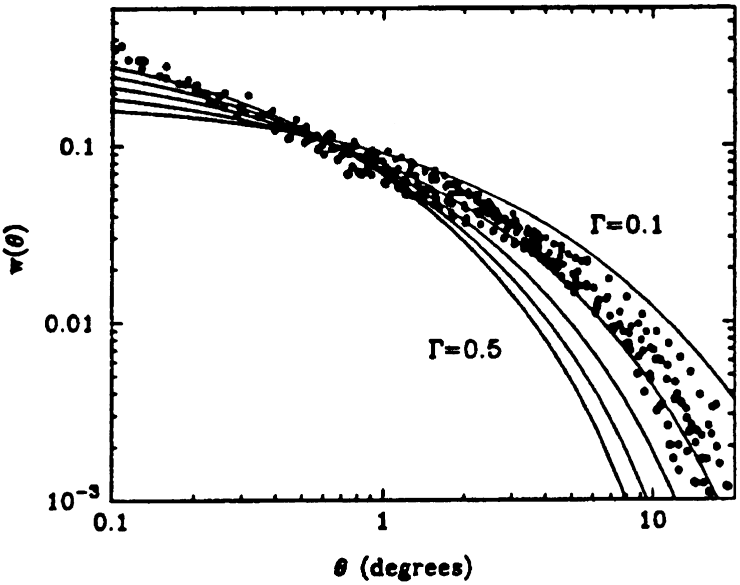

Figure 2. The scaled angular correlation function of galaxies measured from the APM survey plotted against linear theory predictions for CDM models (normalized to $\sigma_8 = 1$ on $8h^{-1}$ Mpc scale) with $\Gamma \equiv \Omega_m h = 0.5, 0.4, 0.3, 0.2$ and 0.1 (Efstathiou *et al.* 1990)

that galaxies are clustered on at least $\lesssim 15h^{-1}$ Mpc scale, with a correlation scale of $r_o(gg) \simeq 5h^{-1}$ Mpc, where $\xi(r) \equiv (r/r_o)^{-1.8} \equiv Ar^{-1.8}$. More recent results support the above conclusions, but show a weak correlation tail to larger scales. The recent two-point angular galaxy correlation function from the APM 2D galaxy survey (Maddox *et al.*, Efstathiou *et al.* 1990) is presented in Figure 2. The observed correlation function is compared with expectations from the cold-dark-matter (CDM) cosmology (using linear theory estimates) for different values of the parameter $\Gamma = \Omega_m h$. Here Ω_m is the mass density of the universe in terms of the critical density and $h \equiv H_0/100$ km s^{-1} Mpc^{-1}. The different $\Omega_m h$ models differ mainly in the large-scale tail of the galaxy correlations: higher values of $\Omega_m h$ predict less structure on large scales (for a given normalization of the initial mass fluctuation spectrum) since the CDM fluctuation spectrum peaks on scales that are inversely proportional to $\Omega_m h$. It is clear from Figure 2, as was first shown from the analysis of galaxy clusters (see below), that the standard CDM model with $\Omega_m = 1$ and $h = 0.5$ does not produce enough large-scale power to match the observations. As Figure 2 shows, the galaxy correlation function requires $\Omega_m h \sim 0.15$–0.2 for a CDM-type spectrum, consistent with other large-scale structure observations.

The power spectrum, $P(k)$, which reflects the initial spectrum of fluctuations that gave rise to galaxies and other structure, is represented by the Fourier transform of the correlation function. One of the recent attempts to determine this fundamental statistic using a variety of tracers is presented in Figure 3 (Peacock and Dodds 1994; see also Landy *et al.*, Vogeley *et al.* 1992, Fisher *et al.* 1993, Park *et al.* 1994). The determination of this composite spectrum assumes different normalizations for the different tracers used (optical galaxies, IR galaxies, clusters of galaxies). The different normalizations imply a different bias parameter b for each of the different tracers [where $b \equiv (\Delta\rho/\rho)_{\rm gal}/(\Delta\rho/\rho)_m$ represents the overdensity of the galaxy tracer relative to the mass overdensity]. Figure 3 also shows the microwave background radiation (MBR) anisotropy as measured by COBE (Smoot *et al.* 1992) on the largest scales ($\sim 1000h^{-1}$ Mpc) and compares the data with the mass power spectrum expected for two CDM models: a standard CDM model with $\Omega_m h = 0.5$ ($\Omega_m = 1, h = 0.5$), and a low-density CDM model with $\Omega_m h = 0.25$. The latter model appears to provide the best fit to the data, given the normalizations used by the authors for the different galaxy tracers. The recent Las Campanas redshift survey has reported excess power on $\sim 100H^{-1}$ Mpc scale over that expected from a smooth CDM spectrum (Landy *et al.* 1996). This is a most important observation that will need to be verified by larger surveys.

The next decade will provide critical advances in the determination of the power spectrum and correlation function. The large redshift surveys now underway, the Sloan and the 2dF surveys, will probe the power spectrum of galaxies to larger scales than currently available and with greater accuracy. These surveys will bridge the gap between the current optical determinations of $P(k)$ of galaxies on scales $\lesssim 100h^{-1}$ Mpc and the MBR anisotropy on scales $\gtrsim 10^3h^{-1}$ Mpc (see McKay, this volume, p. 49). This bridge will cover the critical range of the spectrum turnover, which reflects the horizon scale at the time of matter-radiation equality. This will enable the determination of the initial spectrum of fluctuations at recombination that gave rise to the structure we see today and will shed light on the cosmological model parameters that may be responsible for that spectrum (such as $\Omega_m h$ and the nature of the dark matter). In the next decade, $P(k)$ will also be determined from the MBR anisotropy surveys on small scales ($\sim 0.1°$ to $\sim 5°$), allowing a most important overlap in the determination of the galaxy $P(k)$ from redshift surveys and the mass $P(k)$ from the MBR anisotropy. These data will place constraints on cosmological parameters including $\Omega (= \Omega_m + \Omega_\Lambda), \Omega_m,\ \Omega_b, h$, and the nature of the dark matter itself.

Another method that can efficiently quantify the large-scale structure of the universe is the correlation function of clusters of galaxies. Clusters

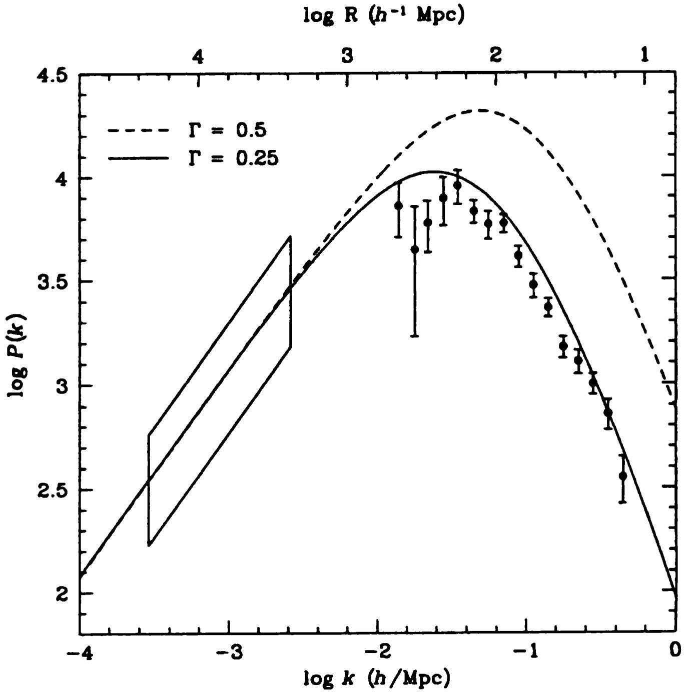

Figure 3. The power spectrum as derived from a variety of tracers and redshift surveys, after correction for non-linear effects, redshift distortions, and relative biases; from Peacock and Dodds 1994. The two curves show the Standard CDM power spectrum ($\Gamma = 0.5$), and that of CDM with $\Gamma = 0.25$. Both are normalized to the COBE fluctuations, shown as the box on the left-hand side of the figure.

are correlated in space more strongly than are individual galaxies, by an order of magnitude, and their correlation extends to considerably larger scales ($\sim 50h^{-1}$ Mpc). The cluster correlation strength increases with richness ($\propto$ luminosity or mass) of the system from single galaxies to the richest clusters (Bahcall and Soneira 1983, Bahcall 1988). The correlation strength also increases with the mean spatial separation of the clusters (Szalay and Schramm 1985, Bahcall and Burgett 1986). This dependence results in a "universal" dimensionless cluster correlation function; the cluster dimensionless correlation scale is constant for all clusters when normalized by the mean cluster separation.

Empirically, the two general relations that satisfy the correlation function of clusters of galaxies, $\xi_i = A_i r^{-1.8}$, are: $A_i \propto N_i$, and $A_i \simeq (0.4d_i)^{1.8}$ (Bahcall and West 1992). (Here A_i is the amplitude of the cluster correlation function, N_i is the richness of the galaxy clusters of type i, and d_i is the mean separation of the clusters.) These observed relations have been compared with expectations from different cosmological models, yielding powerful constraints on the models (see below).

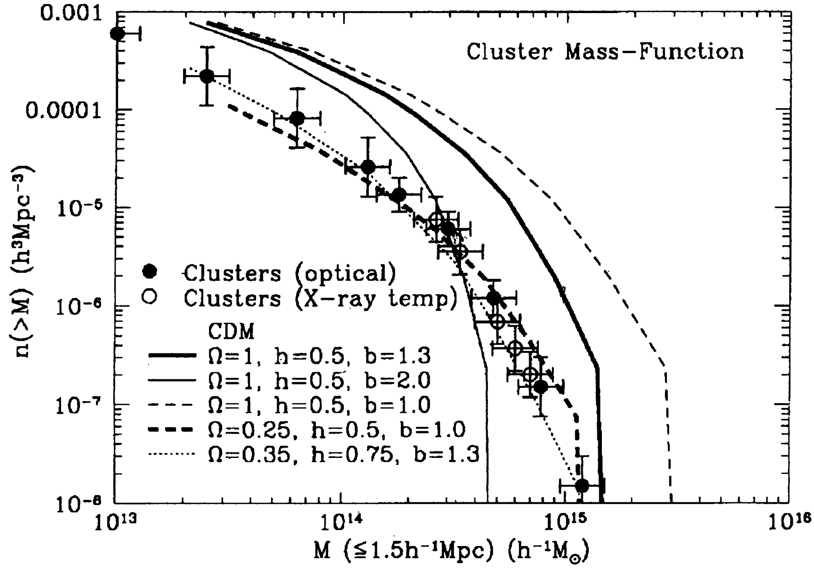

Figure 4. The mass function of clusters of galaxies from observations (points) and cosmological simulations of different $\Omega_m h$ CDM models (Bahcall and Cen 1992, 1993).

The observed mass function (MF), $n(> M)$, of clusters of galaxies, which describes the number density of clusters above a threshold mass M, can also be used as a critical test of theories of structure formation in the universe. The richest, most massive clusters are thought to form from rare high peaks in the initial mass-density fluctuations; poorer clusters and groups form from smaller, more common fluctuations. Bahcall and Cen (1993) determined the MF of clusters of galaxies using both optical and X-ray observations of clusters. Their MF is presented in Figure 4. The function is well fit by the analytic expression

$$n(> M) = 4 \times 10^{-5}(M/M^*)^{-1} \exp(-M/M^*) h^3 \text{ Mpc}^{-3} , \qquad (1)$$

with $M^* = (1.8 \pm 0.3) \times 10^{14} h^{-1} M_\odot$, (where the mass M represents the cluster mass within $1.5h^{-1}$ Mpc radius).

Bahcall and Cen (1992) compared the observed mass function and correlation function of galaxy clusters with predictions of N-body cosmological simulations of standard ($\Omega_m = 1$) and nonstandard ($\Omega_m < 1$) CDM models. They find that none of the standard $\Omega_m = 1$ CDM models, with any normalization, can reproduce both the observed correlation function and the mass function of clusters. A low-density ($\Omega_m \sim$ 0.2–0.3) CDM-type model, however, provides a good fit to both sets of observations (see, *e.g.*, Figure 4).

3. Peculiar Motions on Large Scales

How is the mass distributed in the universe? Does it follow, on the average, the light distribution? To address this important question, peculiar motions on large scales are studied in order to directly trace the mass distribution. It is believed that the peculiar motions (motions relative to a pure Hubble expansion) are caused by the growth of cosmic structures due to gravity. A comparison of the mass-density distribution, as reconstructed from peculiar velocity data, with the light distribution (*i.e.*, galaxies) provides information on how well the mass traces light (Dekel 1994, Strauss and Willick 1995). A formal analysis yields a measure of the parameter $\beta \equiv \Omega_m^{0.6}/b$. Other methods that place constraints on β include the anisotropy in the galaxy distribution in the redshift direction due to peculiar motions (for a review, see Strauss and Willick 1995).

Measuring peculiar motions is difficult. The motions are usually inferred with the aid of measured distances to galaxies or clusters that are obtained using some (moderately-reliable) distance-indicators (such as the Tully-Fisher or $D_n - \sigma$ relations), and the measured galaxy redshift. The peculiar velocity v_p is then determined from the difference between the measured redshift velocity, cz, and the measured Hubble velocity, v_H, of the system (the latter obtained from the distance-indicator): $v_p = cz - v_H$.

The dispersion in the current measurements of β is very large. No strong conclusion can therefore be reached at present regarding the values of β or Ω_m. The larger and more accurate surveys currently underway, including high precision velocity measurements, may lead to the determination of β and possibly its decomposition into Ω_m and b (*e.g.*, Cole *et al.* 1994).

Clusters of galaxies can also serve as efficient tracers of the large-scale peculiar velocity field in the universe (Bahcall *et al.* 1994). Measurements of cluster peculiar velocities are likely to be more accurate than measurements of individual galaxies, since cluster distances can be determined by averaging a large number of cluster members as well as by using different distance indicators. Using large-scale cosmological simulations, Bahcall *et al.* (1994) find that clusters move reasonably fast in all the cosmological models studied, tracing well the underlying matter velocity field on large scales. A comparison of model expectation with the available data of cluster velocities is presented by Bahcall and Oh (1996). The current data suggest consistency with low-density CDM models. Larger velocity surveys are needed to provide more robust comparisons with the models.

4. Dark Matter and Baryons in Clusters of Galaxies

Optical and X-ray observations of rich clusters of galaxies yield cluster masses that range from $\sim 10^{14}$ to $\sim 10^{15} h^{-1} M_\odot$ within $1.5h^{-1}$ Mpc radius of the cluster center. When normalized by the cluster luminosity, a median value of $M/L_B \simeq 300h$ is observed for rich clusters. This mass-to-light ratio implies a dynamical mass density of $\Omega_{\rm dyn} \sim 0.2$ on $\sim 1.5h^{-1}$ Mpc scale. If, as suggested by theoretical prejudice, the universe has critical density ($\Omega_m = 1$), then most of the mass in the universe *cannot* be concentrated in clusters, groups and galaxies; the mass would have to be distributed more diffusely than the light.

A recent analysis of the mass-to-light ratio of galaxies, groups and clusters (Bahcall *et al.* 1995) suggests that while the M/L ratio of galaxies increases with scale up to radii of $R \sim 0.1$–$0.2h^{-1}$ Mpc, due to the large dark halos around galaxies, this ratio appears to flatten and remain approximately constant for groups and rich clusters, to scales of ~ 1.5 Mpc, and possibly even to the larger scales of superclusters (Figure 5). The flattening occurs at $M/L_B \simeq 200$–$300h$, corresponding to $\Omega_m \sim 0.2$. This observation may suggest that most of the dark matter is associated with the dark halos of galaxies and that clusters do *not* contain a substantial amount of additional dark matter, other than that associated with (or torn-off from) the

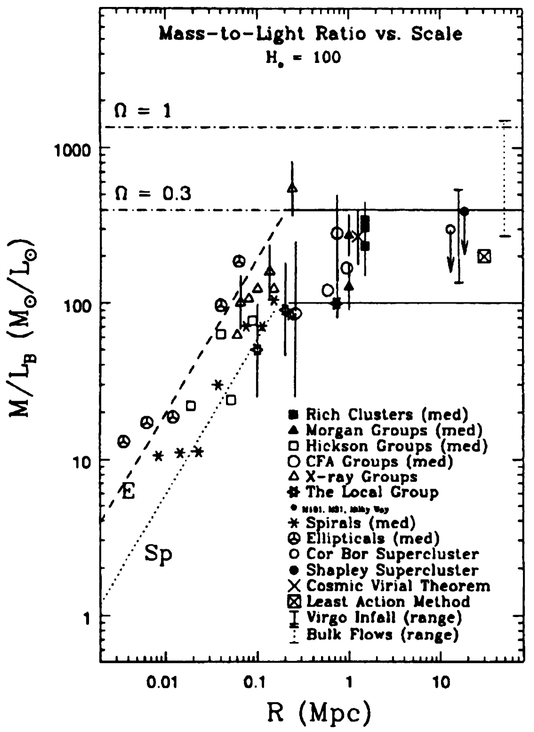

Figure 5. A composite mass-to-light ratio of different systems—galaxies, groups, clusters, and superclusters—as a function of scale. See Bahcall *et al.* 1995 for details.

galaxy halos, and the hot intracluster medium. Unless the distribution of matter is very different from the distribution of light, with large amounts of dark matter in the "voids" or on very large scales, the cluster observations suggest that the mass density in the universe may be low, $\Omega_m \sim 0.2-0.3$.

Clusters of galaxies contain many baryons. Within $1.5h^{-1}$ Mpc of a rich cluster, the X-ray emitting gas contributes $\sim$ 3–10$h^{-1.5}$% of the cluster virial mass (or $\sim$ 10–30% for $h = 1/2$) (Briel *et al.* 1992, White and Fabian 1995). Visible stars contribute only a small additional amount to this value. Standard Big-Bang nucleosynthesis limits the mean baryon density of the universe to $\Omega_b \sim 0.015h^{-2}$ (Walker *et al.* 1991). This suggests that the baryon fraction in some rich clusters exceeds that of an $\Omega_m = 1$ universe by a large factor (White *et al.* 1993, Lubin *et al.* 1995). Detailed hydrodynamic simulations (White *et al.* 1993, Lubin *et al.* 1995) suggest that baryons are not preferentially segregated into rich clusters. It is therefore suggested that either the mean density of the universe is considerably smaller, by a factor of $\sim$ 3, than the critical density, or that the baryon density of the universe is much larger than predicted by nucleosynthesis. The observed baryonic mass fraction in rich clusters, when combined with the nucleosynthesis limit, suggests $\Omega_m \sim$ 0.2–0.3; this estimate is consistent with the dynamical estimate determined above. Future optical and X-ray sky surveys of clusters of galaxies should help resolve these most interesting problems.

5. The Sloan Digital Sky Survey

A detailed description of the upcoming Sloan Digital Sky Survey (SDSS) is presented in this volume by McKay (p. 49). I will not repeat it here. I only summarize that the SDSS is a complete photometric and spectroscopic survey of π steradians of the northern sky, using 30 2048^2 pixel CCDs in five colors (u′, g′, r′, i′, z′), and two spectrographs ($R = 2000$) with 640 total fibers. The 5-color imaging survey will result in a complete sample of $\sim 5 \times 10^7$ galaxies to a limiting magnitude of $r' \sim 23^m$, and the redshift survey will produce a complete sample of $\sim 10^6$ galaxy redshifts to $r' \sim 18^m$ ($z \sim 0.2$), $\sim 10^5$ galaxy redshifts to $r' \sim 19.5^m$ ($z \sim 0.4$) for the reddest brightest galaxies, $\sim 10^5$ quasar redshifts to $g' \sim 20^m$, and $\sim 10^{3.5}$ rich clusters of galaxies.

What are some of the most interesting scientific problems in large-scale structure that the large and accurate Sloan sky survey can address?

- Quantify the clustering (of galaxies, clusters of galaxies, quasars) on large scales using various statistics (power spectrum, correlation function, void-probability distribution, and more).

- Quantify the morphology of large-scale structure (the supercluster, void, filament network).
- Determine the distortion in the redshift space distribution and its implication for the mass-density of the universe.
- Determine the clustering as a function of luminosity, galaxy type, surface brightness, and system type (galaxies, clusters, quasars).
- Determine the clustering properties of clusters (superclustering, correlation function and its richness dependence, power spectrum).
- Study the dynamics of clusters of galaxies. (With the availability of up to hundreds of redshifts per cluster, the mass of clusters can be well determined and compared with X-ray and lensing masses. The cluster mass-function and velocity function will be accurately determined, as well as the M/L and $\Omega_{\rm dyn}$ implications).
- Study the evolution of galaxies, clusters, and superclusters to $z \sim 0.5$, and the evolution of quasars to $z \gtrsim 5$. These should provide important new constraints on cosmology.
- Use all the above to place strong constraints on the cosmological model and Ω, as discussed in the previous sections.

6. Important Future Surveys

What are some of the important surveys needed in order to address the main unsolved problems listed in the introduction? I list below such surveys.

- Optical, infrared, and radio redshift surveys (of galaxies, clusters, quasars, AGNs). These will help solve the quantitative description of large-scale structure, its strength and topology, and the relation among the structures described by different objects.
- X-ray surveys of clusters, quasars, and possibly superclusters. These will allow a good determination of the contribution of the hot gas component in the universe, cluster masses and temperature function, baryon fraction in clusters (and superclusters?), and the evolution of clusters and quasars.
- Gravitational lensing surveys. These will allow the most direct determination of the total mass and mass-density distribution in galaxies, clusters, and large-scale structure.
- Peculiar motion surveys of galaxies and clusters should yield most important constraints on Ω_m and b.
- High redshift surveys, using optical ground based telescopes (Keck), HST, X-rays, and radio, should reveal the important but yet unknown time evolution of structure in the universe. This will provide a fundamental clue to models of galaxy formation and cosmology.

- MBR anisotropy surveys, currently underway, will provide the fluctuation spectrum of the microwave background radiation and hopefully determine many of the cosmological parameters such as Ω, Ω_m, Ω_b, H_o, and the initial spectrum of fluctuations.
- All the above surveys will greatly constrain, and possibly determine the cosmological parameters of the universe (H_o; Ω; Ω_b; q_o; λ).

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