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REDSHIFT SURVEYS OF GALAXIES

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INTRODUCTION

The desire to map the universe in three dimensions has provided the main stimulus for the growth of one of the most successful industries in the history of modern astronomy: the surveying of galaxy redshifts. After the pioneering work of Slipher, Humason, Mayall, and others in the earlier half of the century, the completion of the redshift data base for the *Shapley-Ames Catalog* by Humason et al (1956) and Sandage (1978) yielded the first accurate views of the local universe. In the last fifteen years, advances in detector and spectrometer technology at both optical and radio wavelengths have spurred a tremendous explosion in the galaxy redshift tally. The resulting view of the universe has proved both complex and complicated, and has fostered considerable effort to explain both the topology of the large-scale structure and its origin.

The growth of the redshift industry has paralleled other advances in astronomy, particularly in the past quarter century. The *First Reference*

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Catalogue of Bright Galaxies (de Vaucouleurs 1964) included about 1000 redshifts. Its successor, the *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs et al 1976), contained four times as many. The compilation of 8250 (counting multiple entries for single objects) radial velocities by Palumbo et al (1983) presents, as closely as possible, a complete summary of observational efforts published before 1980.

While the majority of redshifts are obtained via optical spectroscopy, a significant contribution derives from the 21-cm H I line surveys of spirals and gas-rich dwarfs. Surveys conducted in the 21-cm line arrived relatively late as partners in the redshift industry, but improvements in receiver and spectrometer technology eventually led to the participation of radio astronomers. In the early 1970s, only 150 or so galaxies had a measured 21-cm redshift (Roberts 1975). Since then, radio astronomers have rapidly increased their productivity. Of the 30,000 or so galaxies with a measured redshift at the beginning of this decade, those that have been observed at 21-cm account for over 12,000.

By any standards of human activity, the redshift industry is among the most successful, as it can boast a sustained growth rate in excess of 10% per year over its whole 80-year history, and has the potential to maintain its growth for the foreseeable future. Those engaged in this production effort never seem to have enough time left to reflect on achievements, and, more to the point, have little hope of their work having lasting value in review efforts such as this.

With this in mind, we attempt here to give a progress report on the recent advances in terms of the scientific results, technological advances, and the sheer quantity of measurements in the midst of extraordinary growth. In order to cover the wide variety of cosmological problems explored by redshift surveys, we focus on the current horizons, on the comparison of strategies, and on the future promises of technological developments. Only cursory treatment is given to spectral characteristics other than the redshift, and we avoid reviewing quasar studies that lend themselves to a separate review. We have also focused on work of the 1980s rather than providing a complete historical development. Other recent reviews of redshift surveys have been written by Huchra (1988) and Geller & Huchra (1988), while Oort (1983) has summarized earlier results on large-scale structure.

OVERVIEW

Over the last fifteen years, the unfolding picture of the universe has seemed likc a photograph in the process of development, with the detail of structure appearing more vividly as each new compilation is added to the data base.

Until a few years ago, large-scale redshift efforts were concentrated in the northern hemisphere, but recent progress made by southern observers has brought the overall coverage closer to equipartition. At the beginning of 1990, the redshifts of more than 30,000 galaxies were known. The steep growth rate in measured redshifts makes a precise census difficult, especially because a significant fraction of the data base is still in unpublished form. A good part of that fraction is widely if informally circulated. In this section, we present a brief view of the 1990 redshift census as it is available to us. Our compilation of galaxy redshifts includes results of our own redshift surveys, totaling nearly 8000 objects; as well as the Center for Astrophysics (CfA) compilation, as kindly made available to us by J. Huchra in early 1989; the compilations of Richter & Huchtmeier (1989) and of Palumbo et al (1983); the *Supergalactic Plane Survey* of Dressler (1990); the *Southern Sky Redshift Survey* of Da Costa et al (1988), including unpublished southern data made available by L. Da Costa and P. Pellegrini; and a host of smaller data bases. While this census is both inhomogeneous and incomplete to varying degrees from region to region, it nonetheless provides a cursory three-dimensional picture of the large-scale structure of the nearby universe.

Figure 1 displays a heliocentric radial velocity histogram, in 500 km s^{-1} bins, up to 30,000 km s^{-1}. With the cavcats of thc inhomogeneity of the

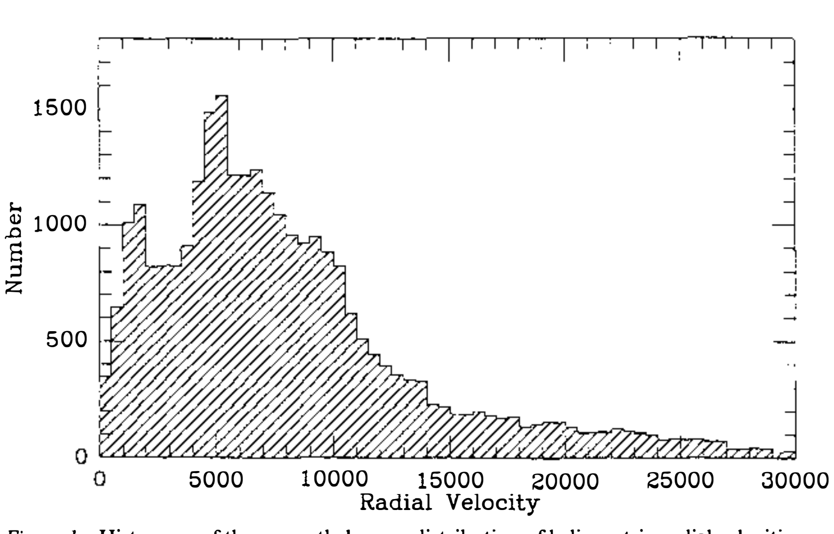


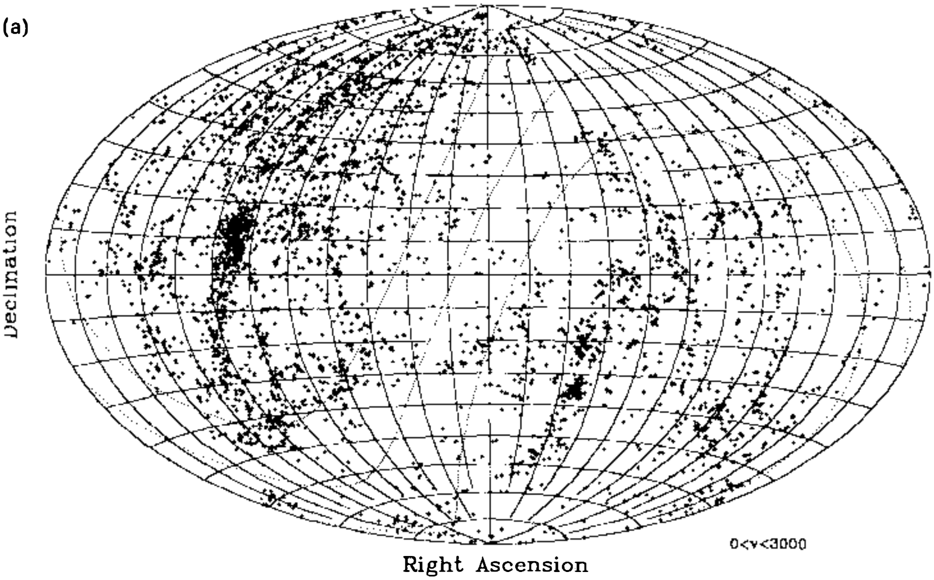
Figure 1 Histogram of thc currently known distribution of heliocentric radial velocities up to 30,000 km s^{-1}.

data base and of its incompleteness (given our lack of access to some unpublished results and their rapid rate of growth), the histogram in Figure 1 resembles the redshift distribution expected of a sample with a limiting magnitude of $m_{pg} \sim 15$, and a depth of about 75 h^{-1} Mpc (where $H_0 = 100h$ km s^{-1} Mpc^{-1}). To complement Figure 1, Figures 2*a* through *f* attempt to provide an impression of the extent of the observational effort. Symbols represent individual galaxies with known redshift, superimposed on a grid of equatorial coordinates in an Aitoff projection. In order to provide equal graphic relevance to each galactic hemisphere, the projection is centered at R.A. = 6^h. Each panel corresponds to a separate, nonoverlapping window of heliocentric radial velocity.

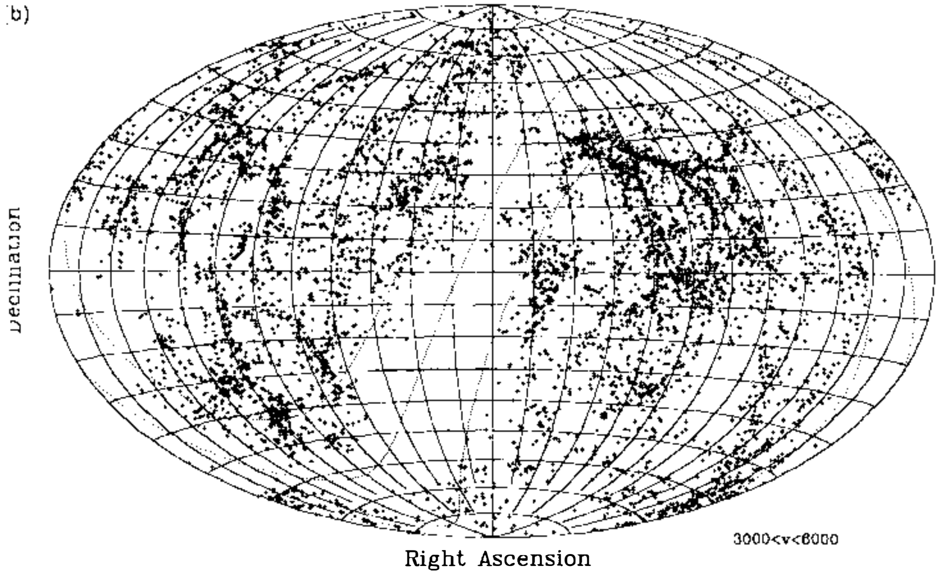
In Figure 2*a*, the large asymmetry between northern- and southern-hemisphere coverage is not as much the result of sample selection or completion bias as of the preference for nearby galaxies to be located in the northern galactic hemisphere towards the central regions of the Local Supercluster. This asymmetry, already recognized a century ago has been understood in terms of the large-scale structure thanks to the pioneering work of G. de Vaucouleurs (1953, 1958). The most conspicuous concentration is of course the Virgo cluster. The supergalactic plane concentration of nearby galaxies is easily visible passing through Virgo. The two large southern clusters between 3^h and 4^h are Eridanus and Fornax. Beyond the Local Supercluster, several features are apparent as seen in Figure 2*b*. North of the equator in the southern galactic cap, the filamentary structure known as the Pisces-Perseus supercluster dominates. The total extent of this supercluster is unknown bccausc it disappears to the North and East into the zone of avoidance. The Hydra and Centaurus clusters, which are nearly symmetric to this supercluster south of the equator in the northern galactic cap, are conspicuous in a region under intense scrutiny in searches for the "Great Attractor". In panel 2*c*, the Pisces-Perseus supercluster begins to fade, while the extensive enhancement associated with the Coma/A1367 clusters becomes dominant near the north galactic pole. The deeper sampling along the Center for Astrophysics constant-declination slices becomes particularly noticeable here.

Figure 2 Sky distribution of galaxies with measured redshifts in different velocity windows. The displayed grids are equal-area Aitoff projections of equatorial coordinates centered on R.A. = 6^h. Individual objects are shown. Solid grid lines are plotted each hour in Right Ascension and each 10° in Declination. Dotted lines trace the galactic latitudes $b = 0°$, $-20°$, and $+20°$. The redshift windows corresponding to each panel are: (*a*) $V_{\odot} < 3000$ km s^{-1}; (*b*) 3000 km s^{-1} $< V_{\odot} <$ 6000 km s^{-1}; (*c*) 6000 km s^{-1} $< V_{\odot} <$ 9000 km s^{-1}; (*d*) 9000 km s^{-1} $< V_{\odot} <$ 12,000 km s^{-1}; (*e*) 12,000 km s^{-1} $< V_{\odot} <$ 15,000 km s^{-1}; (*f*) $V_{\odot} >$ 15,000 km s^{-1}.

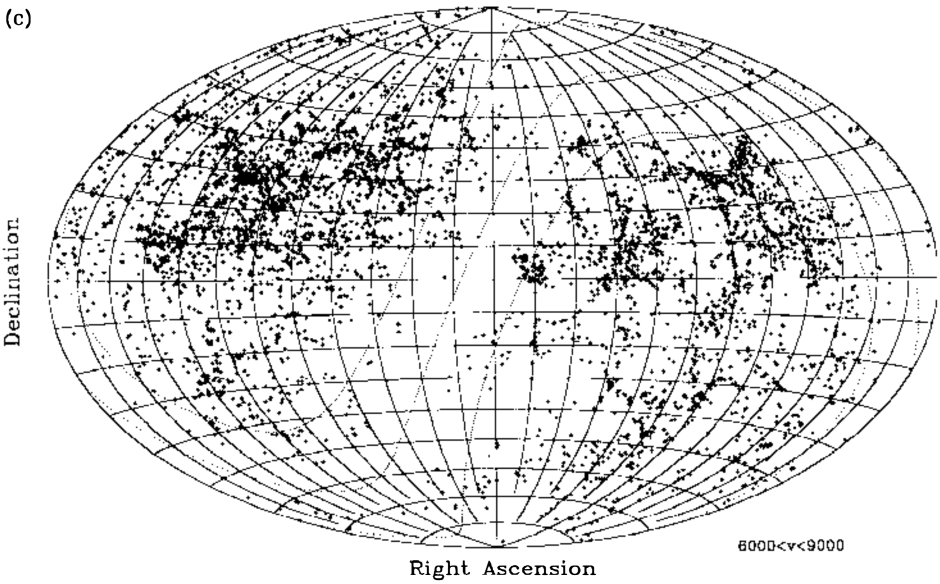
(a)


Declination
0<v<3000
Right Ascension

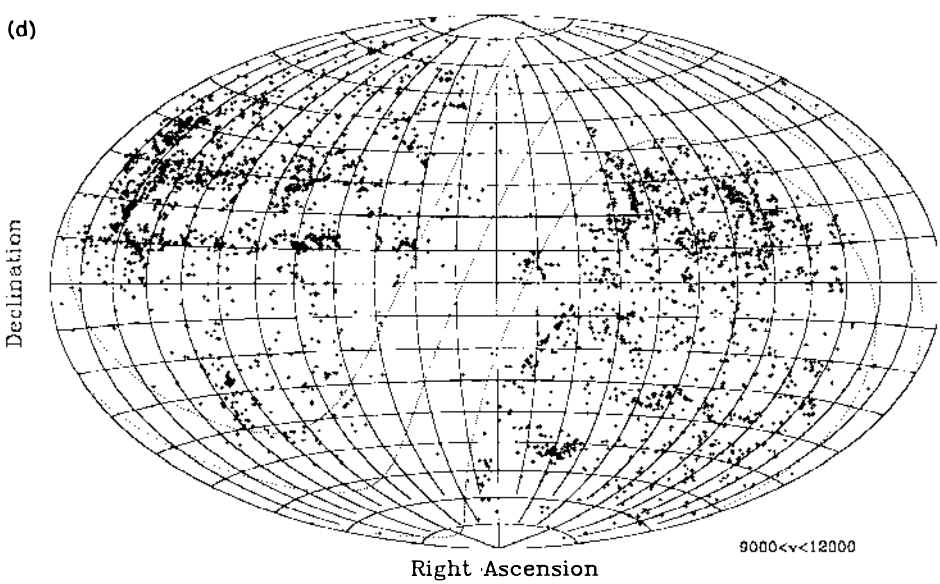
(b)


Declination
3000<v<6000
Right Ascension

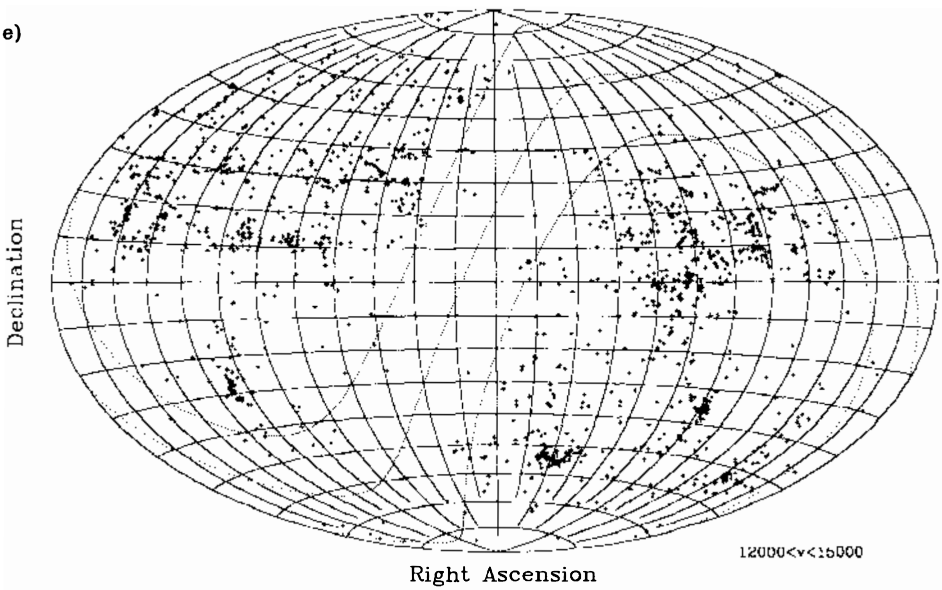
(c)


Declination
6000<v<9000
Right Ascension

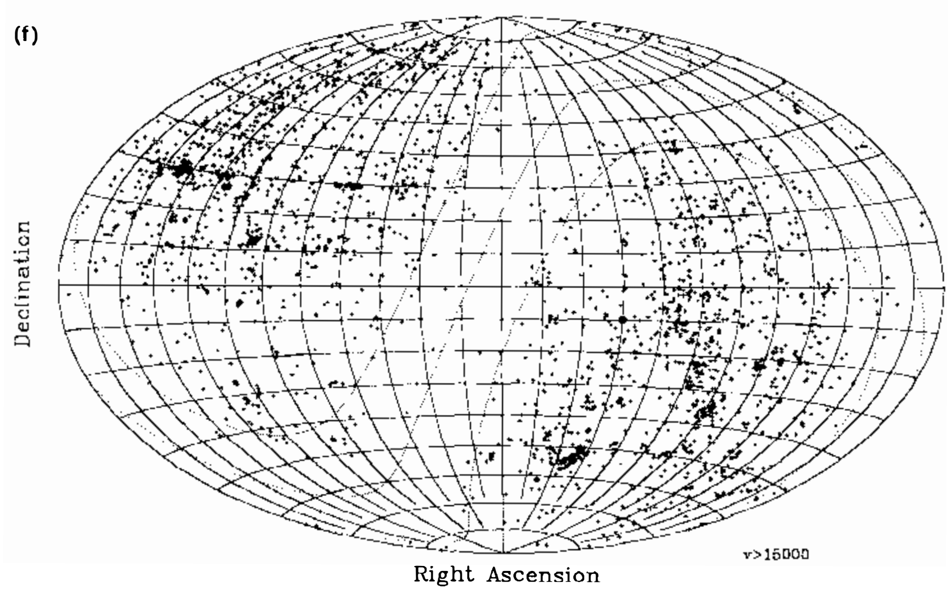
(d)


Declination
9000<v<12000
Right Ascension

e)


Declination
12000<v<15000
Right Ascension

(f)


Declination
v>15000
Right Ascension

In Figure 2*c* as in the following ones, another detail becomes prominent, i.e. the different depths with which the two hemispheres have been sampled. Southern samples, although rapidly growing in scope and depth, are still somewhat shallower than northern ones by about half a magnitude. The depth and completeness of available galaxy catalogs also varies, contributing to the inhomogeneity in the sampling across the sky (Lynden-Bell & Lahav 1988). One of the least-well covered regions is that between $-2°$ and $-18°$ in declination: although to the north of it, galaxian taxonomy is well represented by the *Uppsala General Catalogue* (UGC: Nilson 1973) and by the *Catalogue of Galaxies and Clusters of Galaxies* (CGCG: Zwicky et al 1963–68), and to the south by the *ESO Uppsala Survey of the ESO(B) Atlas* (ESO-UGC: Lauberts 1982) and its recent complement, the *Surface Photometry Catalogue of the ESO-Uppsala Galaxies* (Lauberts & Valentijn 1989), the intermediate region is only served by the *Morphological Catalogue of Galaxies* (MCG: Vorontsov-Velyaminov et al 1962–68), which is less complete and less photometrically and astrometrically accurate than the others.

In Figure 2*d*, the Hercules supercluster extends across the region between $+10°$ and $+40°$ near 16^h. The concentration around A2151, the canonical Hercules cluster, connects via a low-density bridge to the northern enhancement around A2197/A2199. In Figures 2*e* and 2*f*, the greatest concentration occurs in the Horologium region, 35° from the South Pole.

While omissions undoubtedly affect this overview in some details, its general characteristics are representative of the state of surveys within $z < 0.05$. Beyond that value, at this time only small area surveys are significant, a circumstance that will soon change as a result of ongoing or already-planned efforts.

OBSERVATIONS AND SURVEY STRATEGIES

An ideal redshift survey would sample with a well understood selection function a fair volume of the universe. In practice, the approach to a fair volume may yet be unsatisfied, and the selection function is adversely affected by problems of catalog incompleteness, limited accuracy of catalogued parameters, instrumental biases, and loosely defined survey criteria. Those practical concerns often affect the definition of survey strategies by as much as the definition depends on the particular scientific objectives and technology used.

In discussing survey strategies, one should remember that the sky surface density of galaxies to $m_{pg} \simeq 15.5$ is nearly one per square degree, which implies a sky density of ~ 25 to $m_J \simeq 18$, ~ 85 to $m_J \simeq 19$, and so on.

Galaxies are strongly clustered on relatively small scales; the galaxy-galaxy correlation function can be described by a power law $\xi(r) = (r/r_0)^{-\gamma}$, with a slope $\gamma \simeq 1.8$ and a scale-length $r_o \sim 4\text{–}8h^{-1}$ Mpc. To obtain estimates of the fair properties of the galaxian distribution, a survey needs to overcome both the noise that arises from small-number statistics and that from small-scale fluctuations in the distribution itself. The trade-offs are different, depending on the geometry chosen for the surveyed volume and the specific scientific goals of the survey. In some cases, when the goal is the determination of the large-scale behavior of $\xi(r)$, achieving completeness to a flux limit within the sampled volume might not be necessary, as discussed by Kaiser (1986).

Pencil-Beam Surveys

In trying to balance the requirements of depth, completeness, and limited telescope time, pencil-beam surveys are the most economical. The selection of the parameters associated with a pencil-beam survey, such as the beam cross section, is often tied to instrumental constraints, e.g. the size of a spectrograph's aperture plate. In order to overcome the effect of small-scale fluctuations in the galaxian distribution, one would thus ideally choose the cross section of a pencil-beam survey (at its nominal redshift depth) to be comparable to or larger than r_o. The sampling density can then be set by matching the associated sampling error with that arising from the clustering properties and the chosen geometry of the sampled region.

A survey spread over many separate fields can afford to sample deeply in the redshift direction while also covering a large solid angle. Thus a combination of pencil-beam surveys can economically yield information on very large-scale features in $\xi(r)$. On the other hand, topological details that could be investigated with a wide-angle survey tend to be lost. In addition, the approach may complicate the definition of the survey's selection function; for example, a space dependence is introduced by coupling the number of redshifts obtainable per field to the multiplexing factor of a multiobject spectrograph, when the survey field size is comparable to that of the spectrograph. The special niche for discrete field surveys of the pencil-beam variety is in the trailblazing determination of the rough, large-scale properties of the galaxian distribution, ideally followed by more detailed studies over wider solid angles.

KOSS In a series of joint papers, Kirshner, Oemler, and Schechter—later joined by Schechtman (hence KOSS)—, approached the observational study of large-scale structure by sampling almost completely to a fairly deep magnitude limit several widely spaced fields, each about one square degree in size. At the mean depth of their survey, one pencil-beam field is somewhat narrower than r_0, so the structure seen in each tends to be dominated by the small-scale fluctuations in the galaxian distribution. Nonetheless their survey showed considerable deviations from homogeneity on very large scales. In 1981, on the basis of 133 redshifts in three fields $\sim 35°$ apart, KOSS reported the discovery of a large void in Boötes, centered at $cz \sim 15{,}000$ km s^{-1} and extending over 6000 km s^{-1} in the radial direction (see also KOSS 1983). In 1987, a more elaborate analysis confirmed the existence and size of the void (although not as extreme a density contrast as initially reported); they sampled 283 small fields—each 15′ on a side—spread between 13^h30^m and 16^h30^m, $+30°$ to $+70°$, to $m_{lim} \sim 17$. KOSS (1990) are currently extending their discrete sampling approach in a survey that covers the two galactic caps to a redshift of 0.2, to include eventually a total of 10,000 to 20,000 redshifts. The strategy combines the advantages of a multifiber spectrograph with the large field of view of the Las Campanas 2.5-m duPont telescope. They are surveying 200 fields, each $1.5° \times 3°$ in size, covering about 25% of the sky between 10^h15^m and 15^h15^m, 0° to $-18°$, for the northern galactic hemisphere, and between 21^h00^m and 04^h30^m, $-30°$ to $-48°$, for the southern one. They are obtaining their own photometric and astrometric catalog by means of a CCD drift survey. A 60-fiber spectrograph can yield 40 to 45 redshifts of galaxies with magnitudes $16.0 < R < 17.3$, per 2^h exposure, and about 4 fields per night can be observed. By summer 1990, they obtained about 2000 redshifts.

DURHAM-AAT-SAAO Peterson et al (1986) surveyed five high-galactic-latitude UK Schmidt Telescope (UKST) fields, each with an average area of 14 deg^2, widely separated between the equator and $-50°$. To a mean limiting magnitude of about $b_j \sim 17.0$, each field contains about 70 galaxies. This first sample, observed with the Anglo–Australian Telescope (AAT), is commonly referred to as the Durham-AAT redshift survey (DARS). Comprising redshifts of 329 galaxies, it also benefits from high-quality photometric data, obtained digitally on UKST IIIa–J plates. This effort was recently complemented by that of Metcalfe et al (1989), who selected a sample of about 750 galaxies in nine UKST fields, to a depth comparable to that of the earlier DARS, and measured the redshift of every third galaxy in the sample for a total of 264 redshifts. These observations, carried out at the 1.9-m telescope of the South African Astronomical Observatory (SAAO), are referred to as the Durham-SAAO sample. A notable parallel effort, also at the SAAO, concentrates on the southern sky survey field 349, in which Parker et al (1986) reported 107 redshifts to $b_J \sim 16.5$. These studies have concentrated on the determination of the statistical properties of the galaxian distribution, namely the two-point correlation function (Shanks et al 1983, 1989), the galaxy luminosity function (Efstathiou et al 1988), and applications of the cosmic virial theorem (Hale-Sutton et al 1989). The Durham effort has been particularly effective in the study of high-redshift objects, as we discuss below.

GALAXIES AT HIGH REDSHIFT ($z > 0.1$) The study of high-redshift galaxies aims at several goals, mainly: (*a*) the approximation of an elusive fair sample, whereby reliable mean properties of the universe can be obtained; (*b*) the understanding of the evolution of galaxies and of the field luminosity function; and (*c*) a knowledge of the evolution of clusters and their galaxian content. Recent reviews that emphasize particularly aspect *b* can be found in Ellis (1987) and Koo (1988). Because of the low fluxes, redshift surveys employ different strategies for distant galaxies than for nearby ones. At high z, spectroscopic observations can be time consuming (at $z \sim 0.5$, a 200 km s^{-1} quality redshift requires the better part of a night's observing on a 4-m class telescope); the surface density of targets, however, is high, and the use of multiobject spectrographs is well-suited for the task. Alternatively, large numbers of galaxies can be surveyed photometrically, and the broad band spectral information can be used as an indicator of distance, a photometric redshift.

Photometric redshifts The technique, first applied by Baum (1962), is well reviewed by Koo (1986). Observations in many-color passbands yield an estimate of redshift that relies critically on assumptions of each galaxy's stellar population and evolutionary state. Evolutionary models, most notably those of Bruzual (1983 and refs. therein), need to be adopted, and redshifts are derived by best fits of the model spectral energy distributions to the data. Of particular importance to these studies is the identification of the 4000-Å break, a blend of the Ca II H and K and other metal lines whose cosmological potential is discussed by Dressler & Schectman (1987). Koo (1986) finds that two thirds of his photometric redshifts agree with spectroscopic values with an accuracy of ± 0.04 in z for $z \leq 0.35$ and ± 0.06 to $z \leq 0.6$.

Loh & Spillar (1986 and refs. therein) have attempted to apply the results of their photometric survey to place constraints on cosmological parameters. They obtained six-band photometry for a sample of about 1000 galaxies with a median $z \simeq 0.5$ within a pencil beam of 24 μsr, and derived photometric redshifts by best-fitting the location of the 4000-Å break. The number of galaxies observed is essentially the product of the galaxy luminosity function and the volume sampled, and it can be expressed in terms of the mean luminosity density (ϕ^*) and the density parameter Ω. Somewhat controversially, Loh & Spillar (1986) derived a relatively high value of $\Omega = 0.9 \pm 0.3$ for a cosmological constant $\Lambda = 0$.

While the photometric technique of estimating redshifts is an economic one, it remains uncertain, mainly because of evolutionary effects that are themselves the object of study. Photometric techniques allow the probing of faint magnitude regimes ($m_B \sim 23$), and as evolutionary effects become better understood, they might provide a very fruitful tool for the study of large-scale structure.

Spectroscopic redshifts Using a multifiber spectrograph at the AAT, Broadhurst et al (1988) extended an approach similar to that used in DARS to survey 200 galaxies of $20.0 < b_j < 21.5$, in five fields of 200 to 400 arcmin^2 each, at a mean redshift of 0.22. Also at the AAT, Colless et al (1990) used a multislit spectrograph to probe even deeper ($21 < b_j < 22.5$), obtaining 149 redshifts in three fields. With a multislit arrangement at the Kitt Peak 4-m telescope, Koo & Kron (1988) surveyed three fields near the North Galactic Pole; their survey currently includes 401 redshifts (Kron 1990, personal communication). These two complementary efforts have been combined to produce a remarkable view out to $z \sim 0.5$ in the direction of the two galactic poles (Broadhurst et al 1990). The most striking result is the appearance of a strong feature in the clustering at scales of $128h^{-1}$ Mpc. Ongoing efforts will extend the scope of the Durham–AAT and Kitt Peak probes to encompass as many as 30 or 40 pencil beams in both hemispheres, distributed over two patches (each several degrees wide, with one in each hemisphere) for a total of some 1000 redshifts. This combination approach of both pencil beam and sparse sampling emphasizes sensitivity to large transverse structures, since at $z \sim 0.15$, the pencil beam separation is $\sim$10–60 Mpc. The other important thrust of these surveys is the understanding of the evolution of the field luminosity function, as briefly discussed in the last section.

2-D Surveys

As a compromise between the depth of pencil-beam surveys and the relative shallowness of filled, three-dimensional ones, two-dimensional "slice" surveys offer an efficient means of testing the geometry of the galaxian distribution. Once one chooses the depth of the survey by adopting some sort of flux or angular diameter limit (generally imposed by the available catalogs), the angular thickness of the slice can be chosen to match the correlation scale-length at the median distance of the sample. For example, a sample drawn from the CGCG at a magnitude limit of 15.5, the 6° width of a CGCG strip is a convenient approximation of such optimal thickness. At the Harvard-Smithsonian Center for Astrophysics, the most ambitious effort of this nature is underway by Huchra, Geller, and collaborators. While their ultimate goal is the availability of redshifts for all CGCG galaxies with $m \leq 15.5$ and $|b| \geq 40°$ (a sample of about 15,000 galaxies), the completion by slices maximizes scientific returns in terms of the statistical properties of the galaxian distribution. The first of the CfA slices is the 6° by 117° one presented by Huchra et al (1990) and de Lapparent et al (1986) as an extension of the original CfA survey. It covers $8^h \leq$ R.A. $\leq 17^h$ and $26.5° \leq$ Dec. $< 32.5°$. This slice is a magnitude-limited survey of 1100 galaxies, complete to $m_{cgcg} = 15.5$, which crosses some well studied features such as the Coma cluster. Two other slices are also complete, those between $32.5° \leq$ Dec. $< 38.5°$ and $38.5° \leq$ Dec. $< 44.5°$ (see also de Lapparent et al 1988), and several others are nearing completion (Huchra 1990, personal communication). Similar inroads are being made in the completion of their goal in the 20^h to 04^h region. De Lapparent et al (1988) have used complete data on two slices to estimate mean properties of the galaxian distribution.

Continuing work at Dartmouth College in collaboration with the CfA group aims at a deeper view within the region of the first CfA slice, a $1° \times 100°$ strip to $m_B = 17.5$ between $29° \leq$ Dec. $\leq 30°$. The first two reports on this effort, which will eventually include 2500 galaxies, have been given by Thorstensen et al (1989) and Wegner et al (1990a). The deepest completed effort of this type consists of an even narrower (10′) strip across the Coma cluster, extending between 10^h42^m and 15^h28^m and to a magnitude of 18, which has been surveyed by Karachentev & Kopylov (1990) at the 6-m telescope of the Special Astrophysical Observatory of the USSR.

3-D Surveys

Wide-angle surveys designed to sample a specific volume are the best for topological studies of the three-dimensional structure. Such surveys can have practical restrictions imposed by galactic extinction, sky coverage of the telescope used, and limits of the target catalog, usually in apparent magnitude, flux, or diameter, and may also be restricted by morphology or surface brightness constraints on detectability. Each survey must then be evaluated in light of the biases introduced by the selection process. Below, we discuss the major three-dimensional surveys.

THE LOCAL SUPERCLUSTER SURVEY With the goal of improving significantly our knowledge of the structure of the local universe, Fisher & Tully (1981) during the 1970s observed 1787 galaxies at 21 cm, using the 300-foot and 140-foot telescopes at Green Bank and the 100-meter telescope at Effelsberg. Their survey was constrained by loose criteria, biased by their aim to preferentially select nearby galaxies: to $\delta > -45°$, they selected large-angular-diameter objects of spiral or irregular morphology, which upon visual inspection on the Palomar Observatory and Whiteoak Extension Sky Surveys (POSS) appeared to be nearby. While this survey revealed in great detail the structure of the Local Supercluster, it is manifestly incomplete for early morphological types and for distances beyond 1000 km s^{-1}. However this survey, which contributed 1171 new redshifts, was the largest in scope at the time and marked the entrance of the 21-cm line as a main performer in the study of large-scale structure. Tully & Fisher (1987) more recently produced a detailed picture of the structure of the Local Supercluster, with the additional inclusion principally of early-type galaxies of Sandage (1978).

THE CFA SURVEY The first ambitious survey of the past decade was that carried out by Davis et al (1982), known as the CfA survey. This effort aimed at completing (to a limit $m_{cgcg} = 14.5$) a northern-hemisphere sample derived from the CGCG: The boundaries of the survey were $\delta \geq 0°$, $b \geq 40°$, in the northern galactic gap, and $\delta \geq -2.5°$, $b \leq -30°$, in the southern one. The CfA survey compilation (Huchra et al 1983) lists 2401 redshifts; nearly 60% of which were contributed by the CfA group using the 1.5-m Tillinghast reflector at Mt. Hopkins, an instrument since dedicated to the CfA redshift effort. The CfA survey has been used by many authors as the basis of statistical studies of the three-dimensional distribution of galaxies, the distribution and nature of galaxy groups, and the characteristics of galaxy segregation. Huchra (1988) has given a review of the CfA effort and the results derived from it.

THE PISCES-PERSEUS SURVEY The advent of low-noise receivers, coupled with the great collecting area of the Arecibo reflector and advances in spectrometer technology, made possible the pursuit of ambitious surveys with that instrument even within the open competition framework of a national center. Throughout the last decade, Giovanelli, Haynes, and collaborators (Giovanelli & Haynes 1985, Giovanelli et al 1986b, Haynes et al 1988, Giovanelli & Haynes 1989a, Wegner et al 1990b) carried out observations of a sample of approximately 5000 galaxies in the general region of the Pisces-Perseus supercluster, defined by $b \leq 10°$ and $\delta \geq 0°$. This sample includes all CGCG galaxies (to $m = 15.7$) and all those of UGC size 1′ or greater within the sampled region. They inspected and classified non-UGC galaxies on the POSS, and observed at 21 cm (primarily at Arecibo and with the Green Bank 300-foot telescope outside of the Arecibo horizon) all galaxies of types S0a or later. Galaxies of earlier types of unknown redshift and spirals undetected at 21 cm were observed at the McGraw-Hill 2.4-m optical telescope. The overall sample is better than 85% complete; the weakest areas—with completion rates near 65%—correspond to the regions north of $\delta = +35°$ and south of $\delta = 3°$, reflecting zenithal limitations of the Arecibo antenna currently in the process of correction. This effort has contributed new redshifts for approximately 3500 galaxies. Giovanelli (1990) summarizes recent findings. Haynes & Giovanelli (1986, 1988) review analyses of the large-scale structural properties of this region. Topological details are described by Giovanelli et al (1986a), Gott et al (1989), and Ryden et al (1989). Void probability statistics are described by Fry et al (1989). Merighi et al (1986) survey neighboring areas, and Maurogordato et al (1990) map the extension of the supercluster towards southern declinations.

THE SOUTHERN SKY REDSHIFT SURVEY (SSRS) Until late in the 1980s, the redshift coverage of the southern hemisphere was quite uneven, in part because of fewer instrumental resources in the South and in part because a high-quality galaxy catalog was not available until Lauberts' (1982) *ESO Uppsala Survey of the ESO(B) Atlas*. Da Costa et al (1988) combined several efforts, including that of Menzies et al (1989), and produced a catalog of 2028 redshifts that cover 1.75 sr south of $\delta = -17.5°$ and below $b = -30°$. Because Lauberts' catalog was not photometrically complete, da Costa et al selected objects based on an angular size, given by log-$D(0)_{\rm lim} > 0.1$, where $D(0)$ is a diameter in arc minutes, corrected to face-on appearance. A conversion of this limit to one of apparent magnitude would depend upon morphological type, but on the average the depth of this sample is comparable to a blue $m_{\rm lim} \simeq 14.8$. Da Costa et al (1989) have extended the SSRS effort to a second region of $135° \times 10°$, south of $b = -30°$ and at $-40° \leq \delta \leq -30°$. Converting Lauberts' diameters to a magnitude scale, they have surveyed galaxies earlier than Sbc to a blue magnitude limit of 15.1, and are currently reaching completion to 15.5 in that region. A detailed graphic analysis of the galaxian distribution in the southern galactic cap is given by Pellegrini et al (1990).

THE *IRAS* SURVEY The *Infrared Astronomical Satellite* (*IRAS*), which flew in 1983, produced a four-band all-sky catalog of sources. Yahil et al (1986) and Meiksin & Davis (1986) independently used positions and fluxes of galaxies in the catalog to show the existence of a dipole anisotropy in the far infrared source counts that points within about 30° of that measured for the cosmic microwave background. This result suggested that, over very large scales, the *IRAS* galaxies trace the mass that might be responsible for the Local Group's peculiar motion. Because *IRAS* fluxes are little affected by galactic extinction, a reliable nearly all-sky sample can be produced. Yahil (1988) reviews the extension of this effort, which involves the completion of the redshift data base for the galaxies in the *IRAS* sample. The overall sample, as discussed by Strauss et al (1990), includes 2649 galaxies and covers 87.6% of the sky; the redshift collection has been completed and partly published by Strauss & Huchra (1988), and Dey et al (1990). Parallel efforts along the same lines have been carried out by Lawrence et al (1986) and Leech et al (1988), who chose to concentrate their redshift survey of *IRAS* galaxies to high galactic latitudes.

Sparse Surveys

The power-law behavior of the two-point correlation function of the galaxian distribution is well established. However, the clustering signature carried by this statistical procedure becomes weak at the larger scales, say in excess of 20 h^{-1} Mpc. With increasing scale, structures tend to be found in the linear regime (small $\delta\rho/\rho$); they are therefore more likely to have retained memory of initial conditions. The determination of $\xi(r)$ over very large scales ideally requires both deep and wide-angle redshift surveys. Kaiser (1986) has convincingly argued that a sparse, rather than a complete survey approach, can provide the required accuracy in the determination of $\xi(r)$ at substantial observational economy. Although such an approach has been adopted in the past, Kaiser's note quantifies the parameters desired for optimal sampling. Kirshner et al (1987) took advantage of the pencil-beam and sparse sampling approach in effectively surveying a huge volume with a rather small number of observations, and Metcalfe et al (1989) observed only every third galaxy in their sample. However, the full advantage of the technique can be obtained when a very deep, wide-angle and homogeneous catalog is available, such as those generated by the APM (Maddox et al 1990) and COSMOS (Heydon-Dumbleton et al 1989) machines. The coverage of 4300 square degrees in the south galactic cap by the APM survey has produced a catalog of 2×10^6 galaxies brighter than $b_J \sim 20.5$. A sparse survey aimed at obtaining redshifts for one of every 20 APM galaxies in selected areas is currently under way at the AAT (Loveday 1990, personal communication).

Targeted Surveys

Numerous surveys include objects selected according to criteria that do not conform to flux, size, or spatial completeness; their goals can vary greatly and a brief summary and categorization are difficult tasks. Below we discuss some examples of major surveys of such special objects.

BINARIES AND GROUPS These systems are studied in detail for a variety of reasons: (*a*) because relative velocities of members are small, they provide the loci for the study of environmental effects of a milder nature than those observed in clusters of galaxies; (*b*) the distribution of mass can be probed beyond scales accessible by sampling rotation curves; and (*c*) the understanding of their dynamics can lead to insights in the frequency of mergers, the circumstances associated with starburst phenomena, and in other evolutionary concerns. The production of binary and group catalogs is a sort of cottage industry, initially carried out on the basis of angular separation and size criteria and, as more redshift data have become available, via the application of more sophisticated group-finding algorithms. Central contributions are the catalogs of binaries of Karachentsev (1983 and refs. therein) and Turner (1976). Humason et al (1956) and Sandage (1978) first identified groups in redshift catalogs, while variations on the "friends-of-friends" algorithm have been used by Press & Davis (1982), Huchra & Geller (1982), and Morgan & Hartwick (1988), and the dendogram method introduced by Materne (1978) has been most notably applied to generate a catalog of nearby groups [Tully (1987)]. Notable among the numerous analyses of binary and group properties are those of Peterson (1979), White et al (1983), Schneider et al (1986), Schweizer (1987 and refs. therein), Maia et al (1989), Ramella et al (1989), Soares (1989, based on a catalog developed by van Albada, cf. in Soares 1989), and Zepf & Koo (1989).

ISOLATED GALAXIES Isolated galaxies are thought to provide the most reliable statistical reference to study global properties of galaxy populations, unaffected as they might be by environmentally driven evolutionary processes. Several catalogs of isolated galaxies have been produced using varying criteria; the one most used is that of Karachentseva (1973). Haynes & Giovanelli (1984) and Davis & Seaquist (1983) have reported 21-cm results on subsamples of Karachentseva's catalog of, respectively, 324 and 113 galaxies.

DWARFS, LSB, AND EMISSION-LINE GALAXIES The determination of the faint end of the luminosity function, the understanding of galaxy formation, evolution processes and the effects of environment on the latter, and establishing whether segregation phenomena related to properties such as luminosity, surface brightness, or gas content are at work, have motivated many surveys of special objects. Surveys of low-surface-brightness dwarf systems have been carried out mainly via 21-cm line spectroscopy principally at Arecibo: Hoffman et al (1987) in the Virgo cluster region, Thuan and collaborators for an all–northern sky survey of UGC dwarfs (Thuan & Seitzer 1979a,b; Schneider et al 1990); Bothun et al (1985), Eder et al (1989), Salzer et al (1990), and Thuan et al (1987) for the investigation of surface brightness and morphological segregation with local galaxian density. A search for faint Local Supercluster members prompted a 6-m telescope survey of 92 blue galaxies by Karachentsev (1984) who, in addition to identifying 28 new supercluster members, also first suggested the existence of a 70 h^{-1} Mpc feature in the galaxian clustering spectrum. An exhaustive compilation of low surface brightness dwarf galaxies has been produced by Karachentseva & Sharina (1988).

Markarian and collaborators (1981 and refs. therein) at the Byurakan Observatory surveyed 15,000 deg^2 of sky with objective–prism plates to obtain the best known sample of active galaxies. Efforts towards obtaining redshifts for this sample have been ongoing at the 6-m telescope of the Soviet Academy of Sciences (Markarian et al 1988a,b and refs. therein). Stepanian (1985) has reported on the Second Byurakan survey and on the space distribution of galaxies associated with this effort. Salzer et al (1989) have similarly reported reshifts for the University of Michigan objective-prism survey. Searches for emission-line galaxies that might populate low density regions in the galaxian distribution have been carried out by Tifft et al (1986), Moody et al (1987), and Weistrop & Downes (1988). Salzer (1989) has analyzed more generally the relationship between large-scale structure and emission-line objects.

ZONE OF AVOIDANCE Galactic extinction exceeds half a magnitude for about one fifth of the extragalactic sky at optical wavelengths, where catalogs of galaxies become severely incomplete. The task of mapping the nearby universe in those regions thus relies on painstaking efforts of identification of highly absorbed images in red survey plates (Kraan-Korteweg 1990 and refs. therein) or on the application of a combination of radio and infrared techniques. The *IRAS* point source catalog has served as a source of extragalactic candidates in the zone of avoidance, with 21-cm line observations used to establish a redshift. In this mode, several surveys have helped reduce the margins of darkness of the zone of avoidance, e.g. Dow et al (1988), Pfleidcrer et al (1981), Chamaraux et al (1990), and Lu et al (1990). Kerr & Henning (1987) have carried out blind 21-cm searches in the galactic plane. Complete coverage of the zone of avoidance at 21 cm has often been invoked as a desirable goal. However, the necessary investment of telescope time is exceptionally large, and blind radio searches out to redshifts of 0.03 can realistically be limited to only restricted patches of sky.

SUPERCLUSTERS AND VOIDS Several studies targeted selected areas for redshift survey work, aiming at the definition of three-dimensional features in the large-scale structure of the galaxian distribution. They have often been stimulated by features in the projected galaxy counts, suggestive of coherent density enhancements. Oort (1983) reviews the early work. Kraan-Korteweg (1986) gives a useful catalog of 2810 galaxies in the

Local Supercluster. The Coma region continues to receive special attention (Gavazzi 1987, 1989; Gregory et al 1988; Tifft & Gregory 1988), as have regions around Hercules (Freudling et al 1988), Corona Borealis (Postman et al 1988), Hydra-Centaurus (da Costa et al 1986, 1987), Centaurus-Pavo (Fairall 1988), Horologium-Reticulum (Lucey et al 1983, Chincarini et al 1984), and Lynx-Ursa Major (Giovanelli & Haynes 1982, Focardi et al 1986). Particularly notable in terms of the sample size are the surveys of the Cancer region by Bicay & Giovanelli (1986a,b, 1987), which included a contribution of 644 redshifts, that of the Great Attractor (Dressler 1988, 1990), which included 1314 redshifts, and those ongoing at Nançay [Chamaraux (personal communication) is completing a survey of MCG late spiral galaxies between $0° > \delta > -18°$, while Fouqué (personal communication) is targeting a similar sample of ESO galaxies south of $\delta = -18°$]. Haynes & Giovanelli (1990a) have presented 300-foot observations of 304 galaxies, mainly north of $+38°$, that complement their Arecibo supercluster survey work. Rood (1988) recently reviewed the efforts directed at the description of voids in the galaxian distribution. More recently, Pellegrini et al (1989) surveyed void regions in the southern galactic cap, and Burns et al (1988) and Willick et al (1990) studied voids in the Pisces region.

Observations of Clusters

Clusters of galaxies are the largest structures in the universe that unambiguously appear dynamically bound. They can thus provide estimates of the mass distribution over scales on the order of several Mpc. The density perturbations that give rise to the formation of clusters and allow them to decouple from the Hubble expansion have very long growth times, and most clusters have not yet attained the degree of dynamical equilibrium that is accompanied by a smooth, spheroidal appearance. Thus, the understanding of their dynamical state necessitates having rich kinematical information in order to determine cluster morphology and membership, and eventually to disentangle substructures from one another and yet obtain statistically sound estimates of the characteristics of each. Although important contributions were made through the years, especially in the study of rich clusters like Coma, until the relatively recent work of Kent & Gunn (1982) for the Coma cluster and Kent & Sargent (1983) for the Perseus cluster, no truly detailed study was available. Several other clusters have since been studied in comparable detail, i.e. with samples that include a few hundred redshifts per cluster, among them the nearby systems Virgo, Centaurus, and Hydra I = A1060 and (thanks to multiobject spectrographs) several more distant clusters.

COMA, PERSEUS, AND VIRGO Kent & Gunn (1982) assembled a data base of about 300 radial velocities in Coma, complete to $m_{cgcg} = 15.7$ within 3° of the cluster center, and to $m_{cgcg} = 15.0$ within 6°. Their discussion of distribution models for the galaxies and for the mass indicated a core radius of 170–200 h^{-1} kpc (8.5′–10′), a total mass within the inner 3.5 h^{-1} Mpc (~3°) of 1.5×10^{15} h^{-1} $M_{\odot}$, a mass to light ratio $M/L_B \sim 360$ h, and that the matter distribution was not significantly different from that of the galaxies. Hughes (1989) critically analyzed their models and those presented in morc recent work. This analysis confirmed the results of Kent & Gunn (1982).

In spite of the low galactic latitude and high extinction of the Perseus cluster—which exceeds half a magnitude at the cluster center—187 redshifts of cluster members were available to Kent & Sargent (1983). At 5470 km s^{-1}, Perseus has the highest velocity dispersion among nearby clusters (1300 km s^{-1}). Its global parameters are comparable to those of Coma: a core radius of 170 h^{-1} kpc (11′), a virial mass of 1.7×10^{15} h^{-1} $M_{\odot}$, and a mass to light ratio $M/L_V \sim 600$ h.

In the case of Virgo, a large redshift data base has currently been accumulated. The major recent contributions have been made by Karachentsev & Karachentseva (1982), Huchra (1985), and Hoffman et al (1987, 1989). Huchra compiled existing data and completed a sample of 471 galaxies within a 6° radius from M87 to a limiting magnitude of $m_{cgcg} = 15.5$. Binggeli et al (1985) produced a catalog of 2096 galaxies in an area centered on the Virgo cluster, based on 2.5-m duPont telescope plates. Using this catalog, Hoffman and coworkers (1989 and refs. therein) observed (at 21-cm at Arecibo) all dwarf irregular galaxies brighter than $b_T = 17.0$—a sample of nearly 300 objects. H I observations are also available of all 100 or so bright spirals deemed to be cluster members. Overall, redshifts are known for over 400 Virgo cluster members, which constitute the highest level of detail and completeness recorded for any cluster. Binggeli et al (1987) have written a comprehensive morphological and kinematical study of this cluster.

OTHER CLUSTERS A detailed study of the Centaurus cluster (based on about 180 cluster members) was presented in a series of three important papers by Lucey et al (1986 and refs. therein). A2670 has been thoroughly studied by Sharples et al (1988), on the basis of a sample of 220 cluster members. Many other clusters have been studied in some detail—data sets typically include a few dozen members per cluster. Notable among them are: the results of Fitchett & Merritt (1988) for Hydra I (A1060, based on redshift data of 95 cluster members as given by Richter 1987), the work by Fabricant et al (1989) on A2256 (86 cluster redshifts), those by Chapman et al (1988) on A194 (74 cluster members), Ostriker et al (1988) on A539 (86 members), Cristiani et al (1987) on Klemola 22, Soucail et al (1988) on A370, Metcalfe et al (1987) on Shapley 8, Dixon et al (1989) on A2197 and A2199 (based on redshift data of Gregory & Thompson 1984, 1986), and (Bothun et al 1983) on Cancer. Other contributions of considerable interest, albeit of somewhat less wealth in the data base, are available for the clusters A1146 (Melnick & Quintana 1985), A1142 (Geller et al 1984), the Eridanus cluster (Willmer et al 1989), A744 (Kurtz et al 1985), A1099 and A1016 (Chapman et al 1987), AC103 (Sharples et al 1985), A262 (Giovanelli et al 1982), A347 and A1367 (Moss et al 1988), NGC 5846 (Haynes & Giovanelli 1990b), and Klemola 27 (Richter 1984). Significant samples including many clusters have been collected by Vettolani et al (1990), Proust et al (1987, 1988), Rhee & Katgert (1988), Green et al (1988), and Owen et al (1988). Struble & Rood (1987) and Andernach (1990) have prepared recent compilations of redshifts and velocity dispersions for Abell clusters.

Two recent contributions stand out for their statistical wealth. To complement Dressler's (1980) morphological study, Dressler & Schectman (1988a,b) have measured 1268 redshifts in 15 clusters. Most recently, Zabludoff et al (1990) presented an analysis of a compilation of 3250 redshifts for galaxies in 69 nearby Abell clusters (including 359 new redshifts).

MULTIPLEXING The high concentration of bright galaxies found in cluster cores is ideally suited for the opportunities offered by multislit and multifiber devices. Thus, Colless & Hewett (1987) measured 604 radial velocities in 14 rich southern clusters—ranging in redshift from 14,000 to 44,000 km s^{-1}. This approach is representative of modern cluster surveys, such as those of Teague et al (1990), Mazure et al (1989), Batuski and coworkers (personal communication), and Guzzo et al (1990). Teague et al (1990) obtained 1034 redshifts (805 cluster members) in a sample of 10 southern clusters, with samples of more than 100 in 3 of them. Guzzo et al (1990) are completing a redshift survey of 150 clusters extracted from the Edinburgh/Durham Southern Galaxy Catalogue (Heydon-Dumbleton et al 1989), carried out with the EFOSC spectrograph in multislit mode at ESO and the *Autofib* multifiber system at the AAT. This effort should result in a sample of over 2000 redshifts. Such a rapidly growing cluster data base will not only lead to an improved understanding of cluster structure, dynamics, and evolution, but also to a much sounder determination of the clustering properties of the universe at the largest scalelengths.

INSTRUMENTATION AND OBSERVING TECHNIQUES

Traditional work was contributed by single-slit optical spectroscopy, and little needs to be added with regards to this well-established technique (Sandage 1975). New detectors have appeared and data reduction techniques have benefited in the past decade from the definition of new methods (Tonry & Davis 1979, Larsen et al 1983). However, most important progress has been made in the area of multiobject spectroscopy, as well as in that of radio spectroscopy, which we choose to discuss in some detail.

Multiple-Object Optical Spectroscopy

Surveys demand more efficient use of the corrected field of view of a telescope than traditional single-slit spectroscopy needs. As surveys shift towards the study of fainter galaxies with surface number densities larger than a few per square degree, the multiplexing advantage of multiple-object spectrographs (MOSs) encourages long integrations that would be uneconomical for a single objcct. MOSs have developed rapidly in the last decade, and hold the promise for an order of magnitude increase in the growth of the extragalactic radial velocity data base in the near future. We discuss separately advantages and limitations of these techniques, including a brief overview of the first effective MOS, the objective-prism Schmidt. Ellis & Parry (1988) have written an excellent comparative review of multiple-object spectroscopy.

OBJECTIVE-PRISM SPECTROSCOPY Markarian and coworkers (Markarian 1967 and Markarian et al 1981 for other references) conducted a highly successful objective-prism survey using the 102/132-cm Byurakan Schmidt telescope, producing a list of about 1500 objects with ultraviolet continua. This effort has been followed most notably by the Cerro Tololo objective-prism survey carried out with the 61/91-cm Schmidt at CTIO (Smith 1975, MacAlpine & Williams 1981 and references therein). The objective-prism is a quick survey technique, which provides large-scale sky coverage of relatively bright sources ($B \sim 17$ for the Byurakan survey, $B \sim 18.5$ for the Tololo survey) with strong emission lines, whereby multiplexing is obtained thanks to the large field of the Schmidt. The near-UV to blue spectra are of very low dispersion (2500 Å mm^{-1} and 1740 Å mm^{-1} at H_γ, respectively, for the Byurakan and Tololo surveys), and in some of the sources they can yield a redshift determination with an error of about 0.03 in z. This accuracy is only of moderate interest, at best, in large-scale structure studies. However, Cooke et al (1981) underscore that measurements on UK Schmidt plates of the 4000-Å break can provide radial velocities that are accurate to ~ 1800 km s^{-1} for galaxies with $b_J < 18.7$. Parker et al (1987) propose that this feature can be profitably used in the study of the large-scale distribution properties of early-type galaxies; Beard et al (1986) have adopted a similar technique to obtain estimates of 496 redshifts—accurate to 2000 km s^{-1}—to $m_J \sim 17.8$, in a UKST field in the Indus supercluster region.

OPTICAL FIBER SPECTROGRAPHS Optical fiber spectrographs typically can convey light simultaneously from 10 to 100 sources over field sizes of typically 0.4°–1° in diameter. Thus, a fiber MOS is best suited for the study of sources with surface number densities of 100 deg^{-2} or higher. In earlier systems, the coupling of fibers and source locations in the focal plane was slow and cumbersome. However, the development of automated fiber-positioning devices allows increasingly fast repositioning of the fiber assembly in the focal plane, and thus makes modern multiple fiber spectrographs practical instruments in fields of lower source surface density. The tendency to build devices with increasingly larger numbers of fibers is complemented with that of obtaining systems that can be repositioned readily for different fields in the course of an observing session. Hill (1988) chronicles a highly readable history of the first ten years of multiobject fiber spectroscopy.

The first fiber MOS was developed at the Steward Observatory. Several other systems were built at major observatories in the early 1980s, most notably FOCAP (Gray 1984) for the AAT, OPTOPUS (Lund & Enard 1984) at ESO, and *Nessie* at Kitt Peak (Barden & Massey 1988). These systems rely on the preparation of aperture plates, with holes drilled with high precision at the locations of the target sources. Prior to each observation, the fiber ends must be attached to the plate. The procedure has important limitations, for it demands good quality astrometric information, and therefore considerable advance preparation: The observing programs are not easily adapted to schedule changes made necessary by prevailing conditions, aperture plate changes are very slow, and handling of fibers may produce considerable wear and tear on the fiber ends. As for all MOSs, the exposure times are those necessary for the weakest source in the field. In the late 1980s, new automatic fiber positioning devices were built, such as the MX system at Steward (Hill 1988) and *Autofib* at the AAT (Parry & Sharples 1988). These two systems illustrate two different mechanical approaches to the problem. MX can position 32 fibers over a 45′ field, using 32 independent robotized arms that intrude in the field from its periphery (like fishing poles in a pond). In the case of *Autofib*, a single very fast robot sequentially positions 64 fibers over the 40′ Cassegrain field of the AAT. The fibers enter the field parallel to the focal plane and are kept magnetically in position. Robotized systems have been built or are about to enter operation for most major telescopes. Ingerson (1988) discusses design trade-offs applicable to fiber MOSs, as they led to the decisions affecting the construction of the *Argus* system at the 4-m telescope at CTIO.

Positioning speed is maximized in the MX design: A given configuration can be attainable in slightly over a minute. Positioning via a single robot, as in designs of the *Autofib* type, typically take several minutes. On the other hand, many independent robotized arms get in each other's way, so that the number of fibers can be higher in *Autofib*-type systems: MX, *Argus*, and *Decaspec* at the 2.4-m Hiltner telescope (Fabricant & Hert 1990) can aim respectively at 32, 24, and 10 sources, while *Autofib* and the Norris spectrograph for the 5-m Palomar telescope (Cohen et al 1988) can do so at 64 and 100 sources, respectively. The physical size of the arms in one case, and that of the magnetic buttons used to keep fibers in position in the other, limits the minimum distance at which fibers can be set. In both cases, designs have been obtained where such separation has been reduced to 15″ or less. In some designs, positions of fibers can be seen on the acquisition/guide TV camera and, with multiple-arm systems, interactive autocentering is possible after the source configuration has been roughly acquired. The increasingly good transmission quality of fibers makes it possible to locate spectrographs and detectors in a remote, immobile environment, rather than on the telescope, thereby improving instrument stability and reducing flexure worries. At this time, fiber losses and those related to focal ratio degradation make an observation through an optical fiber slower by approximately a factor of 2 than those made with a long slit (Fabricant & Hertz 1990).

Fibers used in MOSs have wavelength coverage limitations: dry (i.e. pure) fibers transmit well in the red and infrared, not in the blue; wet fibers (which are doped with small amounts of OH^-) transmit well in the blue, but not in the red. Thus, a choice of the usable spectral region is set by the fibers installed in the MOS. Typically, the spectrograph detector is a CCD; spectra from each fiber need to be separated by at least 6–8 pixels from each other, perpendicular to the dispersion direction, in order to prevent contamination of light between fibers. The size of the CCD thus sets an upper limit to the number of fibers in a MOS. Fiber MOS sky subtraction characteristics are restrictive, especially with very faint objects, unless a large fraction of the fibers is devoted to acquiring sky photons.

Fiber MOSs have also been implemented for use with Schmidt telescopes, making the fiber technique attractive for objects with surface-number densities of less than a few per square degree. The notable example is the FLAIR system at the UK Schmidt at Siding Spring (Watson et al 1988), with 35 fibers. Parker & Watson (1990) have reported successful performance of FLAIR with 116 redshifts to a magnitude limit of $m_J =$ 16.8. Current limitations in performance will be greatly improved with the forthcoming 100-fiber system FLAIR-2.

MULTISLIT SPECTROGRAPHS An effective use of the corrected field can also be obtained by placing several slitlets at the positions of desired sources in the focal plane, coupled with an imaging camera with a dispersing element such as a transmission prism in its collimated beam. This technique is restricted to smaller fields of view—those of the imaging camera, which is usually a CCD chip—and provides lower dispersion than that obtained with fiber MOSs. The dispersed sky photons overlapping the object spectrum, as in the case of objective-prism plates, can be avoided by having the slits placed in an aperture plate.

As in the case with fiber MOSs, technical developments toward having automatic positioning of slitlets in the field of view have been pursued. However, this path has not led to a general-purpose instrument configuration yct, as discussed by Ellis & Parry (1988), and the pre-etched aperture plate method is preferred.

Because sky subtraction is generally more effective with slits than with fibers, slit MOSs can target fainter sources, and they can thus simultaneously obtain a fair number of targets in spite of their relatively small fields of view. The EFOSC at the ESO and the Low Dispersion Survey Spectrograph (LDSS) commissioned in 1988 at the ATT represent two successful versions of the slit MOS. The LDSS is endowed with a relatively large field (12′), which, when coupled with a large CCD camera, such as the Tek 2048^2, should allow simultaneous placing of about 100 spectra, as opposed to 25–30 spectra with 1980s variety CCD chips. Colless et al (1990) describe both the instrument and the first results of a deep LDSS redshift survey. Many characteristics of multislit MOSs are better illustrated vis-a-vis those of fiber MOSs.

Several variables determine the relative quality of the performance of fiber and slit MOSs. Among them, the multiplex gain—or the number of spectra that can be acquired—can be higher for fiber than for slit MOSs. The quality of the sky subtraction, on the other hand, tends to be superior in slit MOSs because sky background is acquired in the immediate vicinity of the object (however, some fiber systems like the Norris at Hale and Decaspec at Hiltner, have satisfactory solutions to this problem). The size of the field of view can be much larger in fiber MOSs, which can sample the whole field of view of the telescope rather than just that physically spanned by the detector. Additional concerns involve sensitivity, ease and the agility of operation, and the need for elaborate preparation and versatility.

The inroads made in robotized systems with many dozen fibers and the relaxation of the need for high-quality astrometric data prior to the observations (allowing interactive adjustments to fiber positioning) have been important in making fiber MOSs the systems of promise for the next decade. The lack of agility in the observations and the need for elaborate and sometimes uneconomical preparation required by systems with specially manufactured aperture plates impose the strongest inhibition to their extensive use. To interested outsiders in this field, such as the present writers, it appears that the latest generation of robotized fiber systems with large fiber redundance to guarantee effective probe-to-probe sky subtraction will be the workhorses of the next decade's survey spectroscopy.

Radio Techniques

The 21-cm line of atomic hydrogen is detectable in spiral galaxies, to moderate distances, and with high precision (velocity errors are usually smaller than 10 km s^{-1}). Tifft (1990) has carefully calibrated various 21-cm systems on a sample of 100 galaxies (see also Tifft & Cocke 1988). Lewis (1987) has reported similar high signal-to-noise, high spectral resolution work. In addition to redshift, the 21-cm profile yields from its integrated flux an estimate of the total H I mass within the galaxy, and from its width, a straightforward measure of the maximum rotation velocity. The discovery of a well-defined relation between a galaxy's luminosity and its rotation velocity (Tully & Fisher 1977) has been used extensively to obtain redshift-independent distanccs to galaxies, to obtain estimates of H_0, and to attempt studies of deviations from Hubble flow.

The H I line is a good tracer of tidal encounters and serves as an indirect probe of the sweeping of the cold interstellar medium by hot intracluster gas (Haynes et al 1984, Giovanelli & Haynes 1989b). Concurrent with the construction of the major aperture synthesis facilities, the development of modern multichannel spectrometers, low noise amplifiers, and high-gain feed systems has expanded the volume visible to single-dish 21-cm line surveys. To date, 21-cm redshifts have been measured for some 12,000 objects, while in 1975 that number was less than 150 (Roberts 1975).

The maximum velocity cz at which a galaxy of H I mass $M_{\rm HI}$ and velocity width ΔV can be clearly detected, when observed with a single dish of diameter d, a receiver of system temperature $T_{\rm sys}$, and an integration time t, is

$$cz \sim (10^4\,\mathrm{km\,s^{-1}})\left(\frac{h^2 M_{\mathrm{HI}}}{4.7\times10^9 M_\odot}\right)^{1/2}\left(\frac{\Delta V}{300\,\mathrm{km\,s^{-1}}}\right)^{1/2}\times\left(\frac{d}{100\,\mathrm{m}}\right)\left(\frac{T_{\mathrm{sys}}}{20\,\mathrm{K}}\right)^{-1/2}\left(\frac{t}{5\,\mathrm{min}}\right)^{1/4}.$$

An interference-free five-minute on-source observation at Arecibo can detect a normal Sb galaxy of H I mass $4.7\times10^9 h^{-2} M_\odot$ at $cz \sim 16{,}000$ km s^{-1}. Upon completion of the upgrade currently under way (see next section), the same observation will be possible in between 1/8 and 1/60 of this time, depending on the source's zenith distance.

Not all galaxies contain significant amounts of H I gas. Most notably, elliptical galaxies, at least the majority of them, do not contain detectable amounts of H I (see Wardle & Knapp 1986). Thus redshift surveys conducted via the 21-cm line concentrate on spiral and irregular objects. Galaxies of type S0 and earlier are underrepresented. Furthermore, spiral galaxies in the cores of rich clusters are severely H I deficient (Haynes et al 1984), presumably as a result of recent environmental alteration. Unseen galaxies, rich in H I but optically invisible do not contribute significantly to the mean mass density of the universe (Briggs 1990) and do not fill the voids (Eder et al 1989). On the other hand, spirals constitute the vast majority of galaxies in the field, and late-type, low surface brightness galaxies are H I–rich and even more easily visible to the 21-cm eye than to the optical one. The 21-cm line surveys are thus biased towards late-type, low-surface-brightness objects that preferentially occupy the field. In contrast, the high-surface-brightness objects typically included in magnitude-limited optical redshift surveys show a higher degree of clustering (Davis & Djorgovski 1985, Giovanelli et al 1986a). Radio and optical surveys are thus, to a large degree, complementary (see also Huchra 1987).

Important and comprehensive compilations of H I data have been presented by Bottinelli et al (1982) and more recently by Richter & Huchtmeier (1989 and refs. therein). Aperture synthesis observations are typically shallower than single dish ones, but the gain in spatial resolution adds critically to understanding the kinematics and distribution of the gas, as shown in recent studies of the Virgo cluster (Guhathakurta et al 1988, Cayatte et al 1990). Multiple-object spectroscopy with single radio dishes is more difficult. The limited field size and large receiver horns in focal planes of paraboloids or, in the case of Arecibo, the long line feeds, do not lend themselves to multiplexing. Focal plane arrays can be built for paraboloids, but their usefulness lies more in mapping extended emission regions or in blind searches than in targeted survey work.

Future Developments

The technical advances of the past decade have enormously increased the efficiency of conducting spectroscopic observations of galaxies. While detector and spectrometer technology will likely maintain its progressive pace, the construction of numerous large-aperture optical telescopes equipped with multiple-object spectrographs promises enormous growth. The emphasis in radio astronomy will be on large centimeter-wavelength apertures with good interference rejection over wide bandwidths. Here we discuss a few specific major projects foreseen for the coming decade.

OPTICAL SPECTROSCOPY SURVEY TELESCOPES Two important projects that have the potential for revolutionizing redshift survey work have been defined in great detail. Gunn (1990b) proposes the construction of a Ritchey-Chretien 2.5-m telescope with a large (25% blockage) secondary, a 3°-wide field, and an f-ratio optimized for multifiber spectroscopy and CCD imaging surveys. Because up to $b_J = 19$, the sky density is approximately 85 galaxies per square degree, the telescope should be able to acquire about 500 galaxies per field, which would be accessed by two spectrographs, each fed from fibers from half the field. To that magnitude limit and at a resolving power of approximately 1000, an adequate signal-to-noise ratio could be obtained with an exposure of about one hour. A survey of about 1800 fields—10,300 square degrees—should yield 870,000 spectra within four years. A comparably ambitious photometric CCD transit survey would be even faster than the spectroscopic survey, and both survey tasks could be completed in just over five years.

The Spectroscopic Survey Telescope, proposed by a consortium that includes Pennsylvania State University and the University of Texas adopts a spherical primary, as in the Arecibo antenna, except that the optical reflector will be mounted at a 30° angle to the vertical, on a platform that can rotate in azimuth. Located at the McDonald site in West Texas, the telescope will cover declinations between $-5°$ and $+67°$. At a given configuration, the field of view of the primary will be 12°, which will be accessed by two independent Gregorian subreflectors, each producing a 2′ field of view that can be independently pointed. The main mirror will consist of 85 one-meter spherically figured segments, arranged in a circular frame 10 m in diameter. The light-gathering power of the telescope will be equivalent to that of an 8.5-m diameter single mirror. At low to moderate resolution ($R \sim 500$–100), a spectrum of a twentieth magnitude quasar could be acquired in about 10 minutes (Ramsey et al 1988).

RADIO TELESCOPES Two new projects will have an important impact on 21-cm spectroscopy: the upgrade of the Arecibo antenna and the construction of the new Green Bank telescope (GBT).

In the Arecibo upgrade, which will start in early 1991, spherical aberration correction by the present lossy line feeds will be replaced with a Gregorian subreflector assembly, and a noise-suppressing ground screen will be added around the rim of the primary (von Hoerner 1989). These improvements will increase the absolute gain of the antenna, nearly eliminate vignetting at high zenith angles, allow substantially reduced system temperatures, greatly increase instantaneous observing bandwidths, and add interference-rejection capacity. For applications to 21-cm spectroscopic survey work, these improvements will increase the speed of operation by factors of between 8 and 60 (Giovanelli 1987), albeit with no change of the declination horizon, which restrict the telescope to about one third of the whole sky. Completion of this upgrade is scheduled for 1993.

The GBT, which has a similar development schedule as the Arecibo upgrade, will have a paraboloidal aperture of modern design capable of reaching any declination north of about $-45°$. The unblocked character of its 100-m aperture will permit an extremely high gain-to-system temperature ratio for its size: about 0.13–0.15 Jy^{-1}, which is only a factor of two or less times smaller than that of the current much larger aperture Arecibo antenna (0.23 Jy^{-1}). Its wide sky coverage (especially South of the Equator), extremely high sensitivity to fairly extended, low H I surface brightness objects, and high interference rejection characteristics underscore its promise.

AN EVOLVING PICTURE OF THE UNIVERSE

Topology and Fair Samples

A common experience to those who analyze the properties of redshift samples has been that of verifying that the largest traceable inhomogeneities in the galaxian distribution escape through the boundaries of the sampled region, raising the question of what is a fair sample of the universe. To some degree, the measure of fairness for a sample depends on the statistical tools that are to be applied to determine its properties. While the scale length of the galaxy-galaxy correlation function $\xi(r)$ is about the same in any sample (hovering near $r_0 = 5\ h^{-1}$ Mpc), the sizes of the largest structures in 2- and 3-D surveys, be they voids, or connected high density regions, are nonetheless comparable to those of the sampled volumes, typically 20 h^{-1} to 60 h^{-1} Mpc. How much power is there at the large scales, or up to what scale is there any measurable power? A useful analogy to illustrate the ambiguities associated with these measurements might be the determination of the size of oceans on Earth: Although a single body of water can be continuously traced around the planet's surface, we characterize the oceanic structure by a scale length related to the mean separation of continents. Thus, the definition of structure and the measurement of the ocean's size are strongly linked to topology. Topological dccriptions of the galaxian distribution have evolved from the visual, highly subjective appreciation of morphologies in poorly sampled data [see Peebles' (1984) criticism], to more objective numerical approaches applied to progressively richer samples. Panoramic surveys have played an important role in forming our views of the cosmic fabric, as in establishing the prejudices that permeate the numerical approaches that strive for its objective description.

The concept of "supercluster" gained acceptance during the late 1970s. The early studies of the Coma (Chincarini & Rood 1975, Gregory & Thompson 1978), Hercules (Tarenghi et al 1980), and Perseus regions (Gregory et al 1981, Einasto et al 1981) identified features that extend well beyond the boundaries of clusters (see the review by Oort 1983). Kirshner et al (1981) and Davis et al (1982) brought attention to the existence of large, underdense volumes with typical sizes of tens of Mpc that the first CfA slice suggested (de Lapparent et al 1986), might be outlined by a bubblelike galaxian distribution. The Arecibo Pisces-Perseus supercluster survey, on the other hand, revealed the existence of very extensive, linear, filamentlike structures (Haynes & Giovanelli 1986). Topology-discriminating algorithms have been developed (e.g. Gott et al 1987, Ryden et al 1989) and applied to a variety of redshift catalogs (Gott et al 1989); they indicate that, when the galaxian distribution is smoothed to scales as large as the correlation length (r_o), the topology appears spongelike in all samples, an appearance consistent with the standard model in which today's structure has grown from small, random noise fluctuations in the early universe. However, when the galaxian distribution is smoothed to lengths smaller than r_o, the character of the topology shifts towards a meatball rather than a bubble character (i.e. one where volumes are dominated by voids surrounding the enhancements in the galaxian distribution, rather than one where voids are surrounded by closed surfaces of enhanced galaxian density). Reservations on the adequacy of this type of analysis have been expressed by Geller & Huchra (1988).

The ability of a survey to trace a structure from one cnd of the volume sampled to the other does not exclude that the volume has approximated a fair sample. In a cellular network, for example, connected structures that stretch across the sampled region would be seen, no matter how large the sampled volume is, yet a fair sample will be approximated once the volume spans a few cells. Has such a point been reached with nearby, wide-area redshift surveys, or have we not yet run the gamut of large-scale inhomogeneities? The open-ended aspect of the Pisces-Perseus supercluster as surveyed over nearly two radians, and the galaxian distribution on a 360° display that led to the popularization of the feature dubbed "the Great Wall" (Geller and Huchra 1989) suggests that the answer to that question might be negative. Even more impressively, thc finding of Broadhurst et al (1990) of a strong clustering feature with a characteristic scale of 128 h^{-1} Mpc indicates that structure may exist on scales much larger than could have been found by wide-area surveys. Karachentsev (1984) pointed out a similar feature in the clustering spectrum, with a periodicity of about 70 h^{-1} Mpc, although his result, based on only 92 redshifts, was less convincing than that of Broadhurst et al. Given the Karachentsev finding and the pencil-beam nature and huge redshift coverage of the Broadhurst et al survey, the specific value of the periodicity remains statistically weak. Kaiser & Peacock (1990) warn that in pencil-beam surveys, apparent clustering on large scales might result from aliasing of 3-D clustering on small scales, a form of clustering noise. In addition, one should maintain clear perspective that, over volumes of size comparable with those discussed here, several aspects of the galaxian distribution suggest that mean properties have been measured: e.g. the identity of slopes of galaxy counts log $N(m)$ in all directions, known already from the work of Hubble, pose a strong case in favor of fairness over sizes on the order of 100 h^{-1} Mpc. Nonetheless, the perspective that the large-scale structure of the galaxian distribution might be dominated by a network of structures with characteristic scale on the order of 100 h^{-1} Mpc is most tantalizing, and it remains to be established whether the diminishing amplitude of density perturbations with the increasing size of inhomogeneities (found and suggested) can be accommodated with constant slope of the galaxy counts. Much debate will also be focused on the issue of the adequacy of previously favored theoretical and modeling schemes, in the description of the largest scale clustering features. Weinberg & Gunn (1990) have examined the structures expected to be seen when varying magnitude limits are imposed on the numerical results of biased cold dark matter simulations. They propose that wide angle surveys to limiting magnitudes fainter than 16.5 should reveal an even greater wealth of structure. They also underscore the resilience of current theoretical schemes to the threats of, at first sight, hostile observational results: "...the existence of 50–150 h^{-1} Mpc structures is not in itself an argument against gravitational instability, Gaussian fluctuations, and cold dark matter".

The Distribution of Dark Matter

One of the greatest puzzles of modern cosmology is the apparent discrcpancy bctwccn thc amount of visible matter and that inferred from gravitational studies, in particular the increasing discrepancy with increasing scale within bound systems. Mass–to–blue light ratios on the order of 5–20 h are measured in the case of single galaxies, from their internal velocity fields; they double or triple in the case of binaries (Schweizer 1987), reach values several times larger in the case of groups (Tully 1987), and reach a few 100 h in rich clusters. The fast-growing data base of well-sampled clusters yields increasingly consistent values of mass-to-light ratios. For the dozen or so well-defined clusters with the highest numbers of members with known redshift, mass-to-light ratios are in the range $M/L_B \sim 340$–$600\ h$, in solar units. If the matter distribution traces that of the luminous matter, then the interesting implication of the mass density in the universe is that $\Omega \sim 0.2$.

Fueled by the inflationary prediction that $\Omega = 1$, the focus on mapping the large-scale distribution of luminous matter has rapidly been complemented by that of mapping the large-scale distribution of mass. While we have limited this review to redshift surveys and the determination of galaxy distances by the simple application of Hubble's law, a less space-limited review of our understanding of the universe would also encompass the derivation of galaxy distances by means other than the redshift: including the developing applications of the luminosity-velocity relations at both optical and radio wavelengths, through refinements of the original Tully-Fisher and Faber-Jackson relations. The determination of redshift-independent distances (a much more laborious effort than that of obtaining redshifts alone) is currently limited to galaxies within about 10,000 km s^{-1}, as the accuracy of individual distance determinations has not been reduced below 15%. The technique seeks to measure peculiar motions, i.e. the difference between the measured redshift and the redshift-independent distance expressed in km s^{-1}. Such deviations from pure expansion can be related to structure in the gravitational potential field caused by perturbations ($\delta\rho/\rho$) in the density field. A density perturbation will produce a peculiar gravity $\mathbf{g}$ which, in the growing mode and in the linear regime, will produce a peculiar velocity $\mathbf{v}_p = (2/3)[f/(H_o\Omega)]\mathbf{g}$, where $f \sim \Omega^{0.6}$ (Peebles 1980, p. 65). In this mode, the peculiar velocity grows as $t^{1/3}$. Redshift-independent distances rely on measurements of the combination of velocity widths of galaxy spectra and high quality photometry at optical or infrared bands. This work has produced surprising and as yet controversial results, suggesting that the perturbation dynamics of the local universe (within 5000 km s^{-1}) is regulated by few large mass condensations, which do not appear to linearly scale with the large-scale distribution of light. The motions produced by these perturbations would be large, perhaps in excess of 500 km s^{-1}, and they might explain the dipole in the cosmic microwave background radiation field (Smoot et al 1991 and refs. therein). Uncertainties derive primarily from the sparse sampling of peculiar motion yardsticks and from galactic extinction. Burstein (1990) has recently reviewed this field, which, together with that of high redshift surveys, promises to be among the most active in the next decade.

The existence of structure on large scales and sizeable bulk motions would imply significant inhomogeneity in the local mass distribution. Against this unruly backdrop, we might recall that the cosmic microwave background provides a reference of sobering smoothness, as temperature fluctuations $\Delta T/T$ over angular scales of up to a few degrees are unlikely to exceed 10^{-4}.

The Luminosity Function and Field Galaxy Evolution

The galaxy luminosity function at optical wavelengths, $\phi(M)$, is an essential tool in the interpretation of large-scale structure data bases and galaxy number counts, in the derivation of the universe's mean properties such as its luminosity density, and in constraining models of galaxy formation. Binggeli et al (1988) recently reviewed the subject. The two most recent determinations of $\phi(M)$ have been obtained by Efstathiou et al (1988) and de Lapparent et al (1989). The former analyzed the results of the first CfA, DARS, and KOSS surveys, while the latter concentrated on the results of two $6° \times 135°$ slices. Schechter-type fits of the form $\phi(L)dL = \phi^*(L/L^*)^\alpha \exp(-L/L^*)d(L/L^*)$, where L is the luminosity (so L and L^* are related to magnitudes M and M^* in the usual form), yield relatively consistent results; the shape of $\phi(M)$ appears relatively well defined, with $M^*_B \simeq -19.2 \pm 0.1$ and $\alpha \simeq -1.1 \pm 0.1$ for $h = 1$. The errors in the CGCG magnitudes, which form the basic photometric system for the CfA as well as for most northern samples, are a serious concern. The magnitudes contained in the first volume of the CGCG [which partly covers the region in the de Lapparent et al (1989) work] are particularly erratic. An additional source of concern in these determinations is of course related to the issue of fair sampling. The amplitude of $\phi(M)$ is particularly affected by these uncertainties: Efstathiou et al obtain a value of $\phi^* = 0.00156 \pm 0.00034\ h^3\ \mathrm{Mpc}^{-3}$, while the value given by de Lapparent et al is $\phi^* = 0.0020 \pm 0.0005\ h^3\ \mathrm{Mpc}^{-3}$. The mean luminosity density associated with a functional description of $\phi(L)$ as given above is $\rho_L = \phi^*\Gamma(\alpha+2)L^*$, where Γ is the incomplete gamma function. The main uncertainty on ρ_L derives from that on ϕ^*, and its value is $\rho_L = 1.5 \pm 0.4 \times 10^8\ hL_\odot\ \mathrm{Mpc}^{-3}$, adopting the luminosity function parameters of de Lapparent et al. With this determination, a universe with critical mass would have a mass-to-light ratio of $1800 \pm 500\ h\ M_\odot/L_\odot$, a value significantly larger than the best-determined values for clusters of galaxies (typically $< 500\ h\ M_\odot/L_\odot$).

The issue of the local density dependence of $\phi(M)$ has been extensively debated. It has been proved convincingly (Binggeli et al 1988 and refs. therein) in Local Supercluster samples—where morphological types are most reliable—that different morphological types have different $\phi(M)$s, so that $\phi(M) = \Sigma_t \phi_t(M) f_t$, where f_t is the population fraction of galaxies of morphological type t. Efstathiou et al indicate a similar phenomenon, in the sense that galaxies later than Sb are significantly fainter than earlier ones. In addition, $\phi(M)$ may depend explicitly on local density (Giovanelli 1990, Haynes & Giovanelli 1988), although disentangling the morphology-density and the luminosity-density dependences from each other is an uncertain, uneasy task. Related to this issue is the topic of the evolution of $\phi(M)$. It has been known for some time (Kron 1982) that the number-magnitude relation $N(m)$ gets steeper than expected with z. It is not known whether this steepening is caused by a largely enhanced star formation rate in galaxies at $z > 0.1$ or by a population of faint, local dwarfs. Broadhurst et al (1988) have suggested that, out to $z \sim 0.5$, little evolution of the bright end of $\phi(M)$ has occurred, but the faint-end slope of $\phi(M)$ could get steeper with redshift. The count excess would then result from a luminosity-dependent luminosity evolution. Ellis (1990) and Koo (1990) recently reviewed the status of this issue, contributing further cause for skepticism in believing that the bulk of faint galaxies result from nearby, extremely low luminosity dwarfs. Koo also proposes that unless very significant merging of galaxies occurred at high redshift (enough to overcome the volume factor at high z; i.e. if $\Omega = 1$, the volume increases much more slowly with z than if $\Omega = 0$), observations of high redshift galaxies favor a low Ω universe.

Structure and Dynamics of Clusters

Cluster-dynamical properties are tightly linked to initial conditions. In particular the presence of substructure, and its evolution with redshift, may be an important gauge of cosmological models. Cavaliere & Colafrancesco (1990 and refs. therein) suggest that cluster substructure evolves slowly, and that after a Hubble time only a relatively small fraction of clusters will appear relaxed. On the other hand, West (1990 and refs. therein) stresses that a lack of significant substructure in the inner regions of most Abell clusters would imply that they are dynamically relaxed systems at present (see the recent review by Geller 1990). Observations, however, yield growing evidence for substructure. A well studied example of substructure in a cluster is that of Centaurus. On the basis of 180 identified cluster members, Lucey et al (1986) point out that what appears as a single structure projected on the sky, actually does split clearly into two separate components: Cen 30 at $\langle cz \rangle = 3041$ km s^{-1} and Cen 45 at $\langle cz \rangle = 4570$ km s^{-1}, with velocity dispersions of 586 and 262 km s^{-1}, respectively. In each case, a large elliptical galaxy lies near the dynamical center. A model in which the two clumps represent substructures merging together is favored. Bothun et al (1983) convincingly showed that the Cancer cluster is made up of five discrete groups; in this case however, the groups—all characterized by relatively small velocity dispersions—are possibly unbound. Even in the case of Coma (the stereotypical relaxed cluster), close analysis of the galaxian distribution shows central substructure (Fitchett 1990). The importance of abundant radial velocity information in the study of cluster structure and dynamics cannot be overemphasized. In the robust sample of Dressler & Schectman (1988a,b) evidence for substructure is found to be significant in 11 of their 15 clusters. They also suggest that the process of cluster formation may occur over several discrete accretion stages, protracted over the Hubble time. The evidence that clusters are still forming at the present epoch has been reviewed by Sandage (1990).

Some kinematical information suggests that dynamical decoupling of the inner parts occurs in some clusters, i.e. a distinct population of galaxies, slowed down by dynamic friction, becomes actually bound to a cD, which eventually grows by cannibalism (Cowie & Hu 1986). This effect has been studied in A2029 (Bower et al 1988) and in several clusters including A2589 (Bothun & Schombert 1988). Discordant velocities between cDs and the cluster as a whole have been investigated in A2670 (Sharples et al 1988) and A1795 (Hill 1988). Zabludoff et al (1990) find that 8 of 9 cD galaxies have velocities significantly different from the mean cluster value. Some of these results had already been anticipated by Quintana & Lawrie (1982). While they are still somewhat ambiguous in providing hard quantitative information, they do nonetheless underscore (*a*) the condition of yet "unfinished business" associated with the process of cluster collapse at the present stage of evolution of the universe, and (*b*) the necessity of large redshift samples that allow proper interpretation of the dynamic circumstances of any given cluster.

Cluster evolution can also be gauged through changes in their galaxian population. After the early work of Butcher & Oemler (1978), it now appears fairly well established that such evolution has been observed. Three kinds of cluster galaxies are seen with a frequency that increases with redshift (Gunn 1990a): (*a*) blue, narrow emission-line objects possibly quite active in the formation of massive stars, (*b*) active galactic nuclei, such as Seyferts, and (*c*) a population of red galaxies that show Balmer absorption, indicative of the presence of A stars, in addition to an older red population. In the absence of emission lines, the latter galaxies show indications of recent but not ongoing star formation and are dubbed E + A objects (Elliptical + Absorption). While the spectra of most red cluster galaxies are indistinguishable from those of nearby ellipticals, the active galaxies are different from typical nearby spirals, implying that evolution has indeed taken place. The report of a correlation between the active population fraction and the cluster velocity dispersion (Newberry et al 1988), possibly a key to what causes the observed differences between high and low redshift cluster populations, redoubles the need for high-quality dynamic information on distant clusters.

A recent review of the space distribution of clusters of galaxies and its implication on the large-scale structure of the universe has been given by Bahcall (1988a), followed by discussions by Bahcall (1988b), Geller & Huchra (1988), and Sutherland (1988). The cluster-cluster correlation function, $\xi_{cc}(r)$ exhibits amplitudes substantially larger than those of the galaxy-galaxy correlation function, $\xi(r)$, at any separation. Firming our knowledge on the difference between the amplitude of ξ and that of ξ_{cc}—both on the scales over which significant correlation is revealed by the cluster population and on those in which peculiar motions might be implied by redshift elongation of ξ_{cc}—should force important constraints on cosmological scenarios. Cold dark matter schemes, which have dominated the interpretational scene throughout the later part of the decade, may meet difficulties in producing coherent structures on scales exceeding 50 h^{-1} Mpc and peculiar motions as large as 1000–2000 km s^{-1}, as might be indicated by some cluster samples. Sutherland (1988) has illustrated the misleading clues introduced by selection effects, incompletely sampled clusters that might break into several components, and limited redshift information. When these effects are compensated for, the evidence for larger peculiar motions and significant clustering on the largest scales is significantly weakened. The ongoing cluster redshift surveys, together with X-ray selected samples to be derived from orbiting observatories scheduled to be launched in the next decade, should resolve this important issue.

Controversies and Quantization

For many years, the conventional interpretation of the redshift in terms of the Hubble expansion has met with occasional skepticism. Since the time of the Bahcall-Arp debate on the redshift controversy in 1972 (Field et al 1973), some issues (e.g. energy requirements for quasars, infall into clusters) seem to have been resolved to the satisfaction of most. On the other hand, although the evidence is largely circumstantial, individual occurrences of alignments, apparent associations, and extreme velocities may not be easy to explain via the standard approach (e.g. Arp 1987).

Tifft and coworkers (see Tifft & Cocke 1989 and refs. therein) have claimed that quantization effects are present in a variety of redshift data bases, most notably in histograms of the radial velocity separation of members of binary systems. Evidence for this periodicity, mainly the manifestation of a 72.45 km s^{-1} harmonic, has also been found, albeit not compellingly, in several different samples (Sharp 1984, Schneider et al 1986, Croasdale 1989). In examining the redshift distribution of different populations of objects in the Virgo cluster, Guthrie & Napier (1990) find no evidence for quantization in the redshift distribution of dwarf irregulars, but a possible periodicity (slightly different from Tifft's) appears in the power spectrum analysis of the brighter spirals. This effect is significant only with the further assumption that the Local Group is falling directly toward the Virgo cluster, as other solutions will not give results with the same significance.

On the skeptical side of the issue, Newman et al (1989) point out the statistical flaws of periodicity analysis in small-number samples, and Sharp (1990) further suggests that in the absence of statistically significant confirmation, the claimed periodicity is not a physical property of the galaxy pairs. In our opinion, redshift quantization is not yet rigorously proved. However, the verification of redshift quantization is potentially important because it does not fit within the framework of conventional dynamics.

THE REDSHIFT INDUSTRY: A PROMISING PROSPECTUS

Redshift surveys are designed primarily to uncover the detailed three-dimensional structure in the galaxy distribution, to study the dynamics of galaxy aggregates, and ultimately to trace the past history of the development of such structure from primordial perturbations. As evidenced in Figure 2, the gross overall characteristics of the nearby universe are beginning to emerge. The distribution of galaxies is far from homogeneous; galaxies cluster on small scales, and, with less accurate measures, on larger scales as well. The progress made in the past quarter century in delineating the large-scale structure can be impressively realized by a quick review of past *Annual Review* articles on related subjects. In his 1965 article on the *Clustering of Galaxies*, Abell (1965) used the term "second-order cluster" in place of the now familiar "supercluster". While it was still controversial at that time, the concept of large-scale clustering has been proved through the acquisition of numerous redshifts. By 1983, Oort (1983) was able to describe the gross charactcristics of thc nearby superclusters (Coma, Perseus, Hercules, and the Local Supercluster, as well as other suspected ones), to note the equal importance of voids, and to hypothesize the existencc of even larger structure on scales $\sim 100\ h^{-1}$ Mpc. In the same volume, Davis & Peebles (1983) discussed evidence for peculiar motions. In the 1970s, survey work painstakingly led to the acceptance of superclustering—the detail of the structure, rather than merely its existence, had started to emerge. The successful efforts of the 1980s have themselves driven the technological advances, particularly in the development of multiobject spectroscopy, that in turn promise more than one order of magnitude growth in the 1990s. Deep, sky-wide, photometric catalogs will complement the redshift efforts.

The next generation of redshift surveys, including those already underway, should give us the needed insight into the three-dimensional structure, allowing us to confidently refer to a fair sample. The increase in sample size will, in turn, provide more significance to statistical tests used to quantify the large-scale structure, to characterize its topology and scales, and to delineate and ultimately catalog both high density regions and voids. Deep surveys will allow the study of the correlation function on large scales: Does $\xi(r)$ go negative at $\sim 20\ h^{-1}$ Mpc or beyond? Many other questions remain. Is the universe a multifractal? Is there structure on scales larger than $\sim 100\ h^{-1}$ Mpc, and, especially, is there a preferred scale for the largest structures? The mapping of the deviations from Hubble flow will lead to the derivation of the mass distribution contributed by both luminous and dark matter. What is the relationship of galaxies and clusters to the underlying large-scale mass distribution in which they are embedded?

Studies of objects at high redshift will allow us to trace the time evolution of galaxy populations in luminosity, color, and with local density, and to follow the development of large-scale structure and substructure. Ultimately, we should pinpoint the epoch of onset of galaxy formation and may gain understanding of the processes responsible for producing the variety of structures we recognize today. All of this must in the end be reconciled with observations of the cosmic microwave background radiation, itself a target for surveys driven by new technologies for both ground- and space-based research.

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