GALAXY REDSHIFT SURVEYS: 20 YEARS LATER

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ABSTRACT. This year marks the 20th anniversary of the effective beginning of large, systematic redshift surveys of galaxies. These surveys have had a major impact on observational cosmology and on our current understanding of large-scale structures in the Universe. To celebrate this remarkable period some landmark observational results are reviewed and our current understanding of LSS is summarized. Although enormous progress has been achieved in mapping the galaxy distribution to moderate redshifts, many of the questions posed over a quarter of century ago have not yet been convincingly answered and must await the completion of new large scale angle surveys such as 2dF and SDSS. On the other hand, unexpected advances have been made at very high redshifts. After years of searching, well-defined samples of extremely distant galaxies are now available, redshifts are being routinely measured and large programs are planned for the 8-m class telescopes. These ongoing or planned surveys of the nearby and distant Universes promise to provide, within a few years, an extraordinary view of the evolution of galaxies and structures from lookback times approaching 90% of the age of the Universe to the present epoch.

1 Introduction

Redshift surveys of galaxies have been, for the past two decades, one of the most useful tools available for cosmological studies. Since the pioneering work of Gregory and Thomsen (1978) and Sandage (1978), among others, progress has been enormous, with the pace being dictated primarily by advances in technology. A particularly significant early milestone in the edl was the start of the Center for Astrophysics Redshift Survey in 1978, one of the first surveys to replace photographic plates by significantly more efficient detectors, making large-scale surveys possible. Similar systems soon became available at several observatories and the number of surveys, using different samples and observing strategies, flourished in the 80s. New developments in the 90s further increased the data gathering power of surveys, making possible to probe much larger volumes. Combined these surveys have provided a wealth of information regarding the properties of galaxies, system of galaxies and the nature of large-scale structure (LSS) as traced by galaxies. Despite the enormous effort a number of outstanding cosmological questions remain unanswered pointing out the need for even larger surveys. Projects like the Anglo-Australian 2dF and the Sloan Digital Sky Survey (SDSS) represent the beginning of a new era in the edl and promise to provide clear answers to these questions. Another milestone are the ongoing (Steidel, this proceeding) and the planned redshift surveys of the high-z Universe on Keck and VLT which will provide a better understanding of the nature of distant galaxies, their clustering properties and insight into early galaxy and structure evolution.

Over the years the goal of most galaxy redshift surveys have remained essentially the same, namely to obtain redshifts for complete samples over a sufficiently large volume to: 1) study the nature of large scale structure; 2) measure the cosmological density parameter from dynamic measurements on small and large scales; 3) compare observed galaxy distribution to predictions based on N body simulations in an attempt to discriminate among competing theoretical models; 4) compare the galaxy distribution to the mass distribution as recovered, for instance, from the peculiar velocity field of galaxies; and 5) study galaxy biasing on small and large scales.
Even though galaxy redshift surveys alone provide only limited information about the underlying mass fluctuations, they will continue to be essential for probing galaxy biasing and evolution models, complements to the information from probes of the mass distribution such as cosmic microwave, gravitational lensing and cosmic microwave background radiation.

The literature on large-scale structure has grown tremendously and a comprehensive review on the subject would be well beyond the scope of this presentation and can be found elsewhere (e.g., Giovanelli & Haynes 1991, Strauss & Willick 1995). Instead, the aim of this review is to illustrate how our picture of the Universe has evolved over the past two decades with the completion of various surveys targeting different redshift intervals. A few reviewed are the results of quantitative analyses carried out with redshift data to describe galaxy clustering as well as the properties of the galaxy population as a whole.

2 Background

In this section, a brief review is presented of the redshift surveys that have shaped our current understanding of the three-dimensional distribution of galaxies. Over the years the picture has evolved dramatically as data have accumulated. The number of galaxies with redshift measurements has grown by roughly a factor 100 from the sample of 2000 available in 1978. This number is expected to grow even faster now as new data from surveys such as 2dF and SDSS and other large surveys at high-redshift become available.

2.1 Low-z

Three-dimensional redshift surveys, which densely sample the local galaxy distribution, are essential to characterize the properties of galaxies and the nature of the large-scale structures at the present epoch. Dense sampling is critical for studying the morphology of large scale structures, while the number of galaxies and surveyed volume are necessary for detailed statistical analyses. It is important to emphasize that the nearby Universe is in some respects unique. For instance, only nearby can one expect to use the peculiar velocity field of galaxies to map the mass distribution in the framework of the gravitational instability paradigm. Comparison between the galaxy and the reconstructed mass distributions provides a valuable probe of the relation between galaxies and the underlying dark matter, at least on large scales (Dekel 1994, da Costa et al. 1996). Further, one linear theory gives a relation between galaxy density and peculiar velocity, which can be used to derive a velocity field from all-sky redshift surveys. The derived velocity field can be compared to that observed to measure \( \omega_{\text{bias}} = \omega_{\text{bias}} \), where \( \omega_{\text{bias}} \) is the cosmological density parameter and \( b \) is the linear biasing factor (e.g., Davis, Nusser & Willick 1996, da Costa et al. 1998).

Until the mid-70s all the information available to cosmologists was the projected galaxy distribution. Although it was apparent that the distribution was far from homogeneous, nothing was known about the reality of the observed structures in three-dimensions. The pioneering pencil-beam surveys of nearby clusters and surroundings (e.g., Geylony & Thomson 1978) provided the first hint that the galaxy distribution was irregular, motivating wide-angle surveys. Such an attempt was first carried out by Sandage (1978). However, the sample, which had a median radial velocity of 1500 km s\(^{-1}\), was too shallow to probe the nature of the large-scale structures. The CFA Redshift Survey (Davis et al. 1982) was the first wide-angle survey to reach beyond the Local Supercluster. It provided strong evidence that the galaxy distribution was far from homogeneous, showing instead a complex topology made up of large empty regions and clumps. However, the structures were poorly defined because of the sparseness of the sample. The picture that emerged was considerably different than that envisioned just a few years earlier, in which clusters were believed to be rare, isolated regions of high density in an otherwise uniform background. In parallel, the KOSS survey (K irshner et al. 1981), using a
series of pencil-beam surveys, identified a large empty region with an estimated size of 60000 km s$^{-1}$. Pressing the observations to fainter magnitudes, the survey of a thin 6 wide slice was completed (de Lapparent, Geller & Huchra 1986) showing that these empty regions were bound by exceptionally sharp and coherent structures with scales comparable to the linear size of the survey ($100 h^{-1}$ Mpc). However, the slice-like geometry of the survey did not allow one to differentiate between two-dimensional structures or one-dimensional laminae. Further evidence of large coherent structures came from the HIPARCOS Survey of the Perseus-Pisces region (came from the HI Arecibo Survey dimensional filament). Further allowing one to differentiate between like geometries of the survey did not common features of the galaxy distribution. They extend out to a moderate depth ($cz < 15000$ km s$^{-1}$), which allows one to probe a linear scale of the order of $300 h^{-1}$ Mpc.

Figure 1 shows a cross-section of the local galaxy distribution obtained by combining the CFA and SSRS. From the redshift maps alone one finds that large coherent structures appear to be a common feature of the galaxy distribution. Walls and voids, 5000 km s$^{-1}$ in diameter, are seen in every region large enough to contain them. The qualitative picture that emerges is one in which the galaxy distribution consists of a volume-lining network of voids.

Unfortunately, the scope of optical surveys is limited to relatively high galactic latitudes because of the zone of avoidance. Therefore, to extend the sky coverage one must resort to infrared-selected samples. Examples of redshift surveys based on IRAS galaxies include the 12 Jy IRAS Survey (Ediger et al. 1995), QDOT (e.g., Kaiser et al. 1991) and more recently PSCz (Saunders et al. 1998). Although considerably more sparse than their optical counterparts, the main advantage of IRAS galaxy redshift surveys is the uniform and unmatched all-sky coverage. Full sky-coverage greatly simplifies statistical analyses (e.g., power-spectrum analysis, counts-in-cells), bypassing some of the problems associated with edge effects and survey geometry. Equally important is the uniformity of the parent sample, which eliminates some of the uncertainties that have plagued the nearby optical surveys. But, above all, the main contribution of redshift surveys of IRAS galaxies is the fact that only from them can one compute a reliable peculiar velocity field as predicted from the galaxy density field, a key element in understanding the dynamical
Because of the unexpected large size of the structures observed nearby, it became essential to extend the surveys to greater depths. To achieve this goal in a reasonable amount of time, the Stromlo-APM survey (Loveday et al. 1992) used a sparse-sampling technique advocated by Kaiser (1986), ideal for low order statistics, measuring redshifts for about 1800 galaxies randomly drawn at a rate of 1 in 20 from a complete magnitude-limited catalog selected from the APM Galaxy Survey (Maddox et al. 1990a). The survey probes a depth of 200 h^{-1} Mpc, sampling a volume about five times that of the CfA2-SSRS2, at the expense of small-scale information. The data were used to measure the luminosity function of galaxies and their clustering properties on large scales, with the large volume allowing for the sampling of a large number of different structures. Analysis of the radial density variation also showed no evidence of a large local void, one of the proposed explanations for the strong variation of the APM galaxy number counts at the bright end (Maddox et al. 1990b).

All the previous surveys were carried out observing a galaxy at a time. A major progress in redshift surveys came about with the multiplexing capability of multi-object spectrographs. An outstanding example of the benefits of the combination of fiber-fed spectrographs and wide-field telescopes is the recently completed Las Campanas Redshift Survey (LCRS, Scheckman et al. 1996) carried out on the 2.5m du Pont telescope at Las Campanas. The LCRS contains redshifts for over 25,000 R-selected galaxies covering 0.2 steradians in six strips, each 1.5° × 80°, in the south and north Galactic caps. The median redshift of the survey is z ≈ 0.1. Although probing a much larger volume, about 2000 times larger than the combined CfA2-SSRS2 survey, inspection of the redshift maps supports the picture that the galaxy distribution consists of a closely-packed network of voids 5000 km s^{-1} in diameter bounded by thin, large walls, with no strong evidence of inhomogeneities on larger scales.

More recently, other surveys to comparable depth to the LCRS, but adopting different selection criteria and observing strategies, have been completed: the Century Survey (CS, Seliger et al. 1997) with about 1800 galaxies covering 0.03 steradians and the ESO Project Slice (EPS, Vettoni et al. 1997) with about 3,300 galaxies covering 0.008 steradians. Again the large-scale features are qualitatively similar to those seen in earlier surveys. However, both surveys claim to find evidence of inhomogeneities, such as the Corona Borealis supercluster, on a scale of 100 h^{-1} Mpc.

Further progress in this range of...
redshifts will have to await the completion of 2dF and SDSS, which will measure of the order of a million redshifts, providing a complete and unprecedented wide-angle coverage of the galaxy distribution to a depth of about 300h⁻¹ Mpc. The impact that these surveys will have can already be appreciated from the preliminary results of the 2dF survey (Maddox, this proceedings).

2.2 Intermediate-z

Hints for power on very large scales were first detected by the deep BERS (Q roadruner, et al. 1988) pencil-beam survey extending to z = 0.5 in the direction of the Galactic poles. The survey used a collection of narrow probes to map the galaxy distribution over a linear scale of about 2000h⁻¹ Mpc. The observed distribution shows a remarkable regularity exhibiting an alternation of peaks and voids with a typical scale of 128h⁻¹ Mpc. However, follow-up observations in other directions not only do not confirm this regularity but detect power on smaller scales (60h⁻¹ Mpc), in agreement with the results from nearby surveys. In order to verify these claims of large scale power, the ESO-Sculptor redshift survey (ESS, Bellanger & de Lapparent 1995) was designed to have a transverse dimension larger than the galaxy correlation length at the median redshift of the survey (z = 0.3) to assure that the detected structures are not artifacts caused by all-scale clustering, one of the main criticisms to the original interpretation of BERS results. The ESS provided the first detailed map of the galaxy distribution in the redshift interval 0.1 < z < 0.5, which confirmed the existence of voids bounded by thin structures over the entire redshift interval. While important, the ESS confirmed that the voids have a typical size of 60h⁻¹ Mpc, with no evidence for periodic structures on scales of 130h⁻¹ Mpc.

Other deep surveys, extending to even larger redshifts (z < 1), have also been completed but have focused primarily on the direct study of the evolution of the luminosity function, star formation and clustering. Among them are: 1) the Auto-b Redshift Survey (Q. Ilbe et al. 1996) which combines several pencil-beam surveys of magnitude-limited samples (1700 galaxies) spanning a wide range in apparent magnitude down to B = 24, and reaching z = 0.75; 2) the Canada-France Redshift Survey (CFRS, Lilly et al. 1995) containing some 600 galaxies brighter than M_B = -22.5, with a median redshift of z = 0.56, and covering an effective solid angle of 112 arc min². These data have provided one of the first secure evidence of a physical association of galaxies at z = 1 (Le Fevre et al. 1994); 3) the CNOC2 survey (Carlberg et al. 1998) which presently contains about 5000 galaxies with R < 21.5 to z = 0.5, over a total area of 1.5 square degrees.

Like in the past, these first results have motivated different groups to plan ambitious surveys using 8-10m class telescopes such as Keck (DEEP) and VLT (VIMOS) to observe large samples of galaxies (10⁷), probing scales of 100h⁻¹ Mpc at z = 1 (e.g., Le Fevre et al. 1996a). Completion of these surveys will allow one to put together a coherent and self-consistent picture of galaxy and clustering evolution from z = 1 to the present.

2.3 High-z: The new frontier

Perhaps one of the most exciting developments in recent years has been the discovery of a population of luminous, star-forming galaxies at z > 3, using a color criteria sensitive to the presence of the Lyman continuum break (Steidel & Hamilton 1993). Currently, the spatial distribution of these Lyman-break (UV-dropout) objects is being investigated and spectroscopic redshifts have been obtained for about 500 galaxies (Steidel, this proceedings). Preliminary results have led to the discovery of a large structure at z = 3.1, which could indicate that well-developed, large-scale structures exist at even these high redshifts (Steidel et al. 1998).

Another important development is the construction of near-IR spectrographs (e.g., NIRMOS-VLT) to measure galaxy redshifts in the interval 1 < z < 3, where most of the spectral features lie outside the optical window. This will allow to bridge the
gap that currently exists between the low-$z$ ($z < 1$) and high-$z$ ($z > 3$) domains.

3 Quantitative Results: Highlights

Considerable progress has also been made in measuring the properties of LSS and galaxies using the data available from the redshift surveys described above. In general, the results from different surveys are consistent, even though some discrepancies still persist and some basic questions remain unanswered. In this section, our current understanding is reviewed by highlighting some of the main quantitative results.

3.1 Luminosity Function

Perhaps one of the most basic statistic that can be measured from redshift surveys is the luminosity function (LF). It not only provides information about the galaxy population but it is a key ingredient in the analysis of magnitude-limited samples. The importance of determining the local LF is that its overall normalization and faint-end slope directly impact the interpretation of the excess observed in the faint number counts and the amount of evolution required to explain them. Furthermore, the local LF has been used to calibrate or to verify the consistency of semi-analytical galaxy evolution models, which have become a powerful tool for detailed comparisons between data and theory (e.g., Kravtsov, White & Guiderdoni 1993, Lacey et al. 1993). However, despite the enormous estimates of the local LF, there is still considerable debate over its shape and normalization. The nature of the problem is reviewed below using results from the most recent surveys.

The local LF has been independently computed for the CfA2 (Mazurek et al. 1994a) and SSR2 (da Costa et al. 1994a, Mazurek et al. 1998) north and south sub-samples, which altogether probe four different regions of the sky. Comparison of these LFs shows that the shapes are in relative good agreement, especially at the faint-end. However, the derived normalization of the CfA2 north LF is significantly higher than the rest, suggesting a mean galaxy density a factor of two larger in that region. By contrast, the LF measured for the SSR2 south and north are essentially identical, presenting very similar shapes and normalizations, even though they probe distinct volumes and largely independent structures. Their normalization is also consistent with that derived for CfA2 south. There are two possible interpretations for the observed discrepancy: 1) there are significant fluctuations of the galaxy distribution on scales of $100 h^{-1}$ Mpc; 2) there are systematic errors in the magnitude-scale, in particular those given in the Zwicky catalog from which the CfA2 sample is drawn.

The same disagreement is seen when comparing the LF of more distant samples (Ellis et al. 1996, Lin et al. 1996a, Zucca et al. 1997, Geller et al. 1997). In general, the derived luminosity functions fall into two broad categories — those with high (Auto b, CfA2, CS, ESP) and low normalization (SSR2, Stromlo-APM, LCRS). Again, with the exception of the CfA2 (at the bright end) and LCRS (at the faint end) the shapes are, by and large, very similar. These results are puzzling since there is no clear correlation between the samples used and the direction in space or the way the parent catalogs for these samples were created. Possible explanations for the conflicting results include: the existence of a large underdense region in the local Universe, an underestimation of the population of low luminosity galaxies nearby or a rapid evolution of the blue luminosity function at low redshifts ($z < 0.1$).

The local LF has also been examined as a function of morphology (Figure 3) and color using the CfA2 (morphology) and SSR2 (morphology and color) samples. Analyses of these samples show that even locally one observes an excess of blue galaxies at faint magnitudes. It is estimated that the faint-end slope of blue galaxies is $<-1.3$ $M_{\odot}$ (Mazurek & da Costa 1997). In addition, using the complete morphological information available for the SSR2, one finds that early and late-type galaxies have very similar, at LFs $M_{\odot}$ (Mazurek et al. 1998), while the ir-
Figure 2. A comparison of recent measurements of the local LF divided by morphological type. Solid lines and open squares represent the SSRS2; dashed lines represent the CfA Survey and dotted lines represent the Stromb-APM (for details see Marzke et al. 1998).

Regular/peculiar galaxy LF is very steep ($\alpha = 1.81$). These results are in good agreement with earlier findings based on the CfA data (Marzke et al. 1994b) but in clear disagreement with the results of Loveday et al. (1995), probably because of inaccuracies in the identification of ellipticals at faint magnitudes. Similar studies are currently underway at moderate redshifts.

A clear resolution of some of the problems mentioned above will have to await the completion of SDSS which will provide a homogeneous, multi-color photometric data set of the northern sky with complete redshift information.

Recent surveys such as Auto b and CFRS, and now CNOC2, with an extended redshift baseline, have provided for the first time, the means to directly study the evolution of the luminosity function. The CFRS sample has been subdivided into several redshift bins and into two colors. Analysis of these subsamples shows that the redder galaxies exhibit remarkably little evolution, while strong evolution is observed for the bluer galaxies. It is important to note that this evolution is independent of the normalization of the "local" LF since it is determined from the sample itself. Strong evolution of blue galaxies has also been observed in the B-selected sample of Auto b.

3.2 Galaxy Power-Spectrum

The power-spectrum (PS) of galaxies in redshift space has been computed for a number of optical (e.g., Park, Gott & da Costa 1992, Park et al. 1994, da Costa et al. 1994b, Lin et al. 1996b) and infrared surveys (Fisher et al. 1993). The redshift-space PS estimates roughly follow a power-law $P(k) \propto k^n$ with a slope ranging from $n = 2$ on small scales ($< 30 h^{-1}$ Mpc) to $n = 1$ on intermediate scales ($30 h^{-1} < 120 h^{-1}$ Mpc). For nearby samples, such as the combined CfA2-SSRS2, one finds that the PS continues to rise on scales up to $200 h^{-1}$ Mpc. This result has been confirmed by similar analysis of other optical and infrared-selected samples, all showing essentially the same shape, while differences in the amplitude can be as-
cribled to the relative bias between optically and infrared-selected galaxies or between galaxies of different luminosities. These earlier results have been confirmed by the PS computed from the LCRS which shows good agreement with previous calculations on scales \( < 100 \, h^{-1} \) Mpc. On larger scales, the LCRS PS shows a change in slope and strongly suggests that it has detected the turnover. A good fit for the observed PS in redshift space, satisfying the constraints implied by COBE, can be obtained with a open or at nonzero cosmological constant CDM model with a shape parameter \( - h = 0.2 \) with no bias. However, several other models are equally viable (da Costa et al. 1994b, Lin et al. 1996b).

### 3.3 Correlation Function

The two-point correlation function, formally equivalent to the PS, has been the most widely used statistics to quantify galaxy clustering. Analyses of magnitude-limited samples have led to consistent results between nearby surveys (e.g., SSRS2) and those probing volumes more than five times larger and adopting different survey geometry and sampling strategies (e.g., Strom b-APM, LCRS). A summary of these results is shown in Figure 1, where the redshift correlation length \( s \) and the slope of the best power law derived from different samples are compared (e.g., W 111, da Costa & Pellegrini 1998, and references therein). As can be seen there is a remarkable agreement among the optical surveys, except for the CBR2 where peculiar motions near the Great Wall are important. In particular, note that the good agreement between the values found for a wide range of volumes is in marked contrast with what would be expected if the galaxy distribution were a fractal. In some cases the relatively small differences between redshift and real space correlations on intermediate scales (10–100 h^{-1} Mpc) immediately suggest, as in the case of the SSRS2, a low value of \( \theta_{\text{redshift}} \approx 1 \) (e.g., W 111, da Costa & Pellegrini 1998).

While galaxy clustering at the present epoch seems to be well quantified, at least for low-order statistics, work is now concentrated in measuring its evolution and interpreting the results within the hierarchical clustering framework. Until recently such studies were hindered by large uncertainties as they had to rely on the observed two-point angular correlation function and models for the clustering evolution and redshift distribution. However, the availability of an increasing number of samples (CFRS, CNOC2) spanning a large redshift baseline will now provide the means to directly measure the evolution of the correlation function and disentangle the effects of cosmology and galaxy evolution (e.g., Kau mann et al. 1998). Preliminary results from CFRS indicate a strong evolution of the clustering amplitude with redshift up to \( z = 0.6 \) (Le Fèvre et al. 1998). This is at variance with more recent results of Carlberg et al. (1998) based on the CNOC2 data, who found a much weaker evolution. Results from very high redshift surveys are also becoming available (Steddel, these proceedings) and the time evolution of clustering as a function of galaxy properties is within reach.

### 3.4 Higher-order Statistics

Given the complexity of the observed large-scale structure, a complete statistical description of the galaxy distribution requires the use of high-order statistics. To investigate high-order correlations, counts-in-cells have been used to compute the count probability distribution function (P \( \Sigma V \)), from which the Void Probability Function (VPF), \( P (G; V) \), and the normalized skewness \( S_3 \) and kurtosis \( S_4 \) have been derived. These statistics have been used to test the hierarchical relations and to compare data to simulations using optical and infrared-selected samples with complete redshift information (Ogashawara et al. 1991, Lachieze-Rey, da Costa & M归属 1992, Bouchet et al. 1993, Benoist et al. 1998). From the moments of the counts distribution and from the scaling of the VPF one nds that the galaxy distribution satisfies the scaling relations predicted by second-order perturbation theory well into the non-linear regime. However, high-order statistics, such as VPF, have not proven...
to be good discriminants of different cosmological models. Instead, preliminary results suggest that high order moments may be best used to constrain galaxy biasing models, especially for large redshift samples expected from 2dF and SDSS.

3.5 Small-scale Velocity Field

Redshift surveys can provide statistical estimates of deviations of the Hubble flow on small scales, without requiring direct distance measurements of individual galaxies. As discussed by Davis & Peebles (1983) this can be done by examining the correlation function, as a function of the projected separation $r_p$ and redshift separation of pairs. Deviations from concentric circles are due to redshift distortions, which provide information on the distribution function of peculiar velocities of galaxy pairs. On large scales, linear theory relates the rms moment of this distribution to the density parameter and the linear bias parameter $b$. On small scales, the cosmological virial theorem connects the second moment of these parameters.

A analysis of redshift distortions observed the 1.2 Jy IRAS Survey lead to estimates of $-b \approx 0.6$, from the cosmological virial theorem, and $-b_{IRAS} = -0.45$ on scales $10h^{-1}$ Mpc (Fish et al. 1994). A sum ming that the relative bias between optical and IRAS galaxies is $b_{IRAS} - b_{opt} = 1.5$ this result implies that $b_{IRAS} = 0.3$, where $b_{IRAS}$ is the mass mass correlation within a sphere $8h^{-1}$ Mpc in radius. Unfortunately, both estimates suffer from either large systematic errors or large cosmological variance, due to the limited number of independent structures sampled by the nearby surveys. This has been vividly illustrated by the large sample-to-sample variations of the relative velocity dispersion between pairs derived from the combined CMASS-2SSRS2 sample (Marzke et al. 1995). The finding that this quantity shows strong sample-to-sample variations indicates that it is poorly determined within the volume surveyed, being dominated by the shot-noise contribution of clusters. One is forced to conclude that at the present time the small-scale velocity field is not a powerful discriminant among competing cosmological models. Even though new statistics have recently been proposed to overcome the effects of a pair-weighted statistic (Davis, Miller & White 1997, Strauss, Ostriker & Cen 1998), it is clear that for robust measurements considerably larger volumes, sampling a fair number of clusters...
of different richness, are required. This will certainly be possible with the next generation of surveys. It is worth pointing out that the estimates of the scale of galaxy clustering at small scales are consistent with the most recent estimates of the parameter from cosmic inflation (e.g., da Costa et al. 1998).

3.6 Galaxy Properties and Biasing

The large number of galaxies available in the nearby dense surveys has made it possible to examine in greater detail the clustering properties of galaxies of different types. Such studies may contribute to our understanding of the relation between galaxies and LSS and help constrain galaxy biasing models. Recent works based on the SSR S2 (Benoist et al. 1996, W hite 1998, da Costa & Pellagrini 1998) have shown evidence of strong, scale-independent luminosity bias, with more luminous galaxies showing a much stronger correlation than sub-L galaxies. This result is in marked contrast with the findings based on the Strom b-APM survey (Loveday et al. 1995). The scale-independence suggests that this bias may be established at the time of galaxy formation. While several models of galaxy formation predict some degree of luminosity bias ($M_{o} = W h i t e 1995$), none can reproduce the observed dependence on the luminosity. An interesting spin-off of this analysis has been to find that very bright galaxies ($L > 3L_{*}$) show a large correlation length ($15 h^{-1} M_{pc}$), comparable to that observed for clusters (Cappellari et al. 1998). Interestingly, these galaxies are not found preferentially in prominent associations of galaxies such as clusters or even loose groups. One possible interpretation is that these galaxies may be associated with more massive dark halos from an early epoch, which would naturally account for their large correlation length.

Using the SSR S2, one also finds that the relative bias between early and late types is scale-dependent (Figure 4), varying from about 1.4 on small scales to 1 at $8h^{-1} M_{pc}$, which may suggest that environmental effects may play a role. The mean relative bias is found to be $b_{E-b_{s}} = 1.2$. This small value, when compared to previous surveys (e.g., Guzzo et al. 1997), probably reflects the paucity of rich clusters in the surveyed region. Both early and late types separately show a luminosity-dependent bias similar to the sample as a whole further suggesting that the luminosity bias is primordial in nature while the excess clustering of early types relative to spirals on small scales may be caused by environmental effects. The relative bias between red and blue galaxies is similar to that observed between early and late type galaxies. However, it levels off on smaller scales ($4 h^{-1} M_{pc}$) at a constant value of about 1.2. The mean relative bias of galaxies selected by color is greater than when selected by morphology. It is important to emphasize that although galaxy morphology and color are related, the scatter is large. This means that these properties may be considered as independent characteristics with colors reflecting the star formation history of galaxies. These results are in qualitative agreement with theoretical predictions of Kau mann, Numer & Steinmetz (1997). Finally, one finds that the relative bias between optical and IRAS galaxies also varies with scale at least out to $10 h^{-1} M_{pc}$ and shows a strong luminosity dependence. The mean relative bias between optical and IRAS is $b_{o-b_{s}} = 1.5$ in real space.

Additional information on the nature of bias can be extracted by investigating the higher order moments of the galaxy distribution. This type of investigation has been conducted using the two-dimensional APM catalog (Szalay & Frieman 1994) and in three dimensions by Bouchet et al. (1993) using the 12 Jy IRAS Catalog. Moreover, Benoist et al. (1998) have carried out similar analysis by comparing the measured skewness in volume-limited catalogs extracted from the SSR S2. Using the large number of galaxies they measured $S_{3}$ for different volume-limited samples, finding $S_{3}$ scale- and luminosity-independent. As shown in Figure 4, the weak dependence of $S_{3}$ on luminosity is in marked contrast to what would be expected from the strong dependence of the two-point corre-
Figure 4. Linear biasing measures for early/late-type galaxies. Panel (a) shows the variance for different luminosity thresholds while panel (b) shows the relative bias between early and late types as a function of scale (for details see Willmer, da Costa & Pellagrini 1998).

Figure 5. The measured skewness $S_3$ of different volume limited sub-samples (full squares) compared to the expected skewness in the linear bias scenario (open squares). Two estimates of the errors are displayed. For sake of clarity, they are slightly shifted in magnitude. The left error bars are estimated from mock volume limited samples extracted from a standard CDM simulation having the same geometry of the SRS2, and the right error bars are estimated from the bootstrap method (for details see Benoist et al. 1998).
location function on luminosity in the framework of a linear biasing model. This result seems to argue in favor of some degree of non-linear bias.

The information derived from studies of clustering as a function of the internal properties of galaxies such as luminosity, color, morphology and internal dynamics, are essential for understanding the connection between galaxy formation and LSS. The present results are merely a preview of what will be possible with the data from a complete redshift survey of a multicolor sample of galaxies as envisioned by SDSS nearby and the ongoing work at high-redshift.

4 Summary

The progress made by redshift surveys has been truly remarkable and promises to continue to be so in the foreseeable future. We are now in a curious transition period. While some basic questions such as the normalization and faint-end of local LF and the scale of the largest homogeneous regions remain open, information about the clustering properties of galaxies at z > 3 are being studied. Clearly, it is just a matter of time for a more detailed picture of the galaxy distribution and the time evolution of galaxy clustering to emerge. Even though this may not yet provide a definite constraint to the background cosmology, it will certainly provide important data to confront galaxy evolution models and answers to how, where, and when galaxies formed. Even though the scientific goals may have changed, it is clear that redshift surveys will continue to be an important cosmological probe for the next 20 years.

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References

Bellanger, C. & de Lapparent, V. 1995, ApJ, 455, 103
Galaxy Redshift Surveys: 20 years later

Gaztanaga, E. & Frieman, J. A., 1994, ApJ, 437, L13
Geller, M. J. & Huchra, J. P., 1989, Science, 246, 857
Geller, M. G., Kurtz, M. J., Wegner, G., Thorstensen, J. R., Fabricant, D., Marzke, R., Huchra, J. P., Schuli, R., & Falco, E., 1997, AJ, 114, 2205
Giovanelli, R. & Haynes, M. P., 1991, ARAA, 29, 499
Gregory, S. A. & Thompson, L. A., 1978, ApJ, 222, 784
Guzo, L., Strauss, M., Fischera, K., Giovanelli, R., & Haynes, M., 1997, ApJ, 469, 37
Kaier, N., 1986, MNRAS, 219, 785
Kaier et al., 1991, MNRAS, 252, 1
Kau mann, G., White, S. D. M., & Guiderdoni, B., 1993, MNRAS, 264, 201
Kau mann, G., Nusser, A., & Steinmetz, M., 1997, MNRAS, 286, 795
Kau mann, G., Colberg, J. M., Diaferio, A., & White, S. D. M., 1998, astro-ph/9809168
Kashner, R. P., Oemler, A. J., Schechter, P. L., & Shectman, S. A., 1981, ApJ, 248, 57
Lacey, C. G., Guiderdoni, B., Rocca-Volmerange, B., & Silk, J., 1993, ApJ, 402, 15
Lahav-Rey, M., da Costa, L., & Guiderdoni, B., 1992, ApJ, 399, 10
Le Fevre, O., Rampon, D., Hammer, F., Lilly, S. J., & Tresse, L., 1994, ApJ, 423, 89
Le Fevre, O. et al. 1996a, ed. J. Bergen, in "The Early Universe with the VLT", Springer-Verlag, Berlin, p. 143
Le Fevre, O., Huchon, D., Lilly, S. J., Rampon, D., Hammer, F., & Tresse, L., 1996b, ApJ, 461, 534
Lilly, S. J., Tresse, L., & Hammer, F., 1995, ApJ, 455, 108
Lin, H., Kashner, R. P., Shectman, S. A., Landy, S. D., Oemler, A., Tucker, D. L., & Schechter, P. L., 1996a, ApJ, 464, 60
Lin, H., Kashner, R. P., Shectman, S. A., Landy, S. D., Oemler, A., Tucker, D. L., & Schechter, P. L., 1996b, ApJ, 471, 617
Loveday, J., Peterson, B. J., Estathiou, G., & Maddox, S. J., 1992, ApJ, 390, 338
Loveday, J., Maddox, S. J., Estathiou, G., & Peterson, B. J., 1995, ApJ, 442, 457
Maddox, S. J., Estathiou, G., Sutherland, W. J., & Loveday, J., 1990a, MNRAS, 243, 692
Maddox, S. J., Sutherland, W. J., Estathiou, G., Loveday, J., & Peterson, B. J., 1990b, MNRAS, 247, 1P
Marzke, R. O., & da Costa, L. N., 1997, AJ, 113, 185
Marzke, R. O., da Costa, L. N., Pellegrini, P. S., & Willmer, C. N. A., 1998, ApJ, 503, 617
Marzke, R. O., Geller, M. J., Huchra, J. P., & Cowin, H. G., 1994a, AJ, 108, 437
Marzke, R. O., Geller, M. J., Huchra, J. P., & Cowin, H. G., 1994b, AJ, 108, 437
Marzke, R. O., Geller, M. J., da Costa, L. N., & Huchra, J. P., 1995, AJ, 110, 477
Mo, H. J., & White, S. D. M., 1996, MNRAS, 282, 347
Park, C. G., Gott, R. J. W., da Costa, L. N., 1992, ApJ, 392, L51
Park, C., Vogelley, M., Geller, M. J., & Huchra, J. P., 1994, ApJ, 431, 569
Sandage, A., 1978, AJ, 83, 904
Saunders et al., 1998, in preparation
Shectman, S. A., et al., 1996, ApJ, 470, 172
Steidel, C. C., & Hamlin, D., 1993, AJ, 105, 2017
Steidel, C. C., Dickinson, M., Giavalisco, M., Pettini, M., & Kellogg, M., 1998, ApJ, 492, 428
Strauss, M., Ostriker, J., & Cen, R., 1998, ApJ, 494, 20
Strauss, M. A., & Willick, J. A., 1995, Physics Reports, 261, 271
Vettolani et al., 1997, A& A, 325, 954
Vogelley, M. S., Geller, M. J., & Huchra, J. P., 1991, ApJ, 382, 44
Willmer, C. N. A., da Costa, L. N., & Pellegrini, P. S., 1998, AJ, 115, 869
Zucca, E. et al., 1997, A& A, 326, 477