Annu. Rev. Astron. Astrophys. 1992. 30: 613–52

EVIDENCE FOR EVOLUTION IN FAINT FIELD GALAXY SAMPLES

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KEY WORDS: distant field galaxies, redshifts, cosmology

1. INTRODUCTION

By the mid-1930s, Milton Humason had determined a redshift of $z = 0.131$ for the Boötis I cluster and $z = 0.137$ for the Ursa Major II cluster (Humason 1936). The ability to measure light coming from such large distances inspired workers like Hubble & Tolman (1935) to consider whether such data could usefully constrain cosmological models (see Sandage 1988 for a review). The highest redshift in the Humason-Mayall-Sandage list (1956) was $z = 0.201$ for the Hydra cluster—a small gain for two decades of effort. In the 1950s, the question of how the intrinsic properties of galaxies might have evolved was linked to the rapidly developing field of post-main-sequence stellar evolution (Sandage 1961, Crampin & Hoyle 1961), with the conclusion that the overall change in luminosity of the galaxy was expected to be comparable in importance to cosmological effects. At higher redshifts, the distinction between world models should be more apparent, but so too should be the evolutionary changes in the galaxies. To probe cosmological distances, Hubble, Humason, and

0066-4146/92/0915-0613$02.00

Minkowski were obliged to select for the highest luminosity galaxies, namely brightest cluster galaxies and radio sources. Surprisingly, the median redshift in the current faint-galaxy samples is not as high as the highest redshifts already reached in the early 1960s (Minkowski 1961, Baum 1962), despite orders-of-magnitude instrumental gain for faint field galaxy spectroscopic surveys. The recent technological advances have instead given us the opportunity to study typical galaxies at large redshift.

In this review we focus on complete samples of faint field galaxies. By *complete*, we mean that the sample is defined by a quantifiable selection procedure, most commonly by magnitude, and by *field galaxy* we mean a galaxy that is selected without regard for its environment. By *faint*, we mean $B > 19$, limited at about $B = 23$ for spectroscopy and $B = 28$ for direct imaging. These depths are needed to reach redshifts beyond $z \gtrsim 0.1$, or a look-back time of a tenth of the Hubble age of the universe. Such complete samples are necessary for tracking redshift-dependent selection effects; for estimating the volume element as a cosmological test; for determining the galaxy number density as a function of redshift; and for exploring the environment of each galaxy and clustering statistics in general.

In the past decade, several results from faint galaxy samples have received attention because comparisons to expectations yielded surprises. A few examples include counts of fainter galaxies in excess of calculations that do not include evolution; redshift distributions remarkably close to no-evolution predictions; shifts to very blue colors for fainter galaxies; and apparently enhanced fractions of galaxy spectra with strong emission lines. We first present the basic data in the form of counts, colors, and redshifts (Section 2), and we then critically comment on general difficulties in measuring faint or high-redshift objects. We also comment on the models in Section 3 that are needed to interpret such data. Finally, in Section 3.3, we present a relatively conventional yet simple model that appears to describe most of the observations.

Before discussing the data in detail, we emphasize the need to be careful in work that pushes photometry and spectroscopy to faint limits. Besides the possibility that the data are plagued by systematic errors, unrealized selection effects, and incompleteness, the interpretations are susceptible to a variety of other uncertainties. These include 1. our relatively poor knowledge of the basic properties of local galaxies; 2. inaccuracies in the comparison of models to the observations; 3. significant fluctuations due to large-scale structure; and 4. the unknown values of the parameters of the cosmological model.

Redshift-dependent selection effects, in particular, must be carefully evaluated. Lower-luminosity galaxies are favored at fainter apparent magnitudes unless luminosity evolution begins to compensate. In a non-expanding Euclidean universe, the distribution of galaxy luminosities seen in a flux-limited sample would be independent of the given flux limit. The apparent distribution is bell-shaped, peaking at the characteristic absolute magnitude M^*. With expansion, however, a fixed optical band measures the generally lower flux in the rest frame, and lower-luminosity, nearer galaxies are favored. Thus, even though intrinsically faint galaxies are not expected to contribute much to the volume emissivity, they may appear in larger proportions in apparently faint samples, and as a consequence, it is important to establish their local space density with precision before conclusions about evolution can be made.

Another effect is that distant galaxies suffer a strong decrease in surface brightness with increasing redshift, again assuming that evolutionary effects do not dominate. In a band with given λ_{obs} and $\Delta\lambda$, the surface brightness (photon rate per angular resolution element) is proportional to $(1+z)^{-3}$. In the red spectral region, the rest-frame spectrum of a typical galaxy can be approximated as $f_\nu \sim \nu^{-2}$. Thus in the background-limited case, the signal-to-noise ratio is proportional to $(1+z)^{-5}$. The exposure time necessary to reach a fixed signal-to-noise ratio is then approximately proportional to $(1+z)^{10}$. (Detecting galaxies in a red spectral band gains little, since the sky background is brighter.)

The strong reduction in signal-to-noise ratio with increasing redshift is inevitably a major effect in the observability of distant galaxies and in the composition of actual faint samples. Galaxies selected optically at large redshift are likely to be those that have especially high intrinsic surface brightness and especially high luminosity at short wavelengths. We anticipate that a "guillotine" in redshift will apply (Pritchet & Kline 1981, Kron 1989, Phillipps et al 1990, Yoshii & Fukugita 1991, Bohlin et al 1991), such that the actual redshift distribution obtained for an incomplete galaxy sample will be deficient in high redshifts compared with a true distribution in a magnitude-limited sample.

2. FAINT FIELD-GALAXY OBSERVATIONS

2.1 *Galaxy Counts*

2.1.1 TECHNIQUES Charge-coupled devices (CCDs) have extended the practical range of galaxy photometry by several magnitudes, allowing galaxies of even ordinary luminosity to be detected at redshifts greater than unity. Measurements of color, surface brightness, and morphology, and indirect arguments based on the distributions of these quantities, can help constrain models at fluxes that are too faint for spectroscopic work.

Various techniques have been devised for automatically identifying and classifying faint images in digital data. Galaxy images are usually assumed to be contiguous and centrally concentrated, and a search for local maxima then provides a first-cut basis for image detection. To guard against noise peaks, one imposes a lower limit to the number of contiguous pixels that appear above a set threshold. To guard against incompleteness, one sets the threshold as low as possible. Thus, galaxy counts tend not to be strictly magnitude-limited, but rather are limited simultaneously in area and in surface brightness. If the detection area were, say, 2 arcsec^2, and if the threshold in surface brightness were 3×10^{-3} of the B-band sky background, then galaxies with measured $B = 28.5$ could be detected. The magnitude is then measured in some way that maintains a particular signal-to-noise ratio, or allows a relatively convenient interpretation of the results, or has some other desirable attribute. *Isophotal magnitudes* are computed by integrating the flux above a chosen surface brightness threshold; *aperture magnitudes* are computed within an area of fixed size; quasi-total or *asymptotic magnitudes* attempt to collect close to all the light; and a number of other schemes have also been tried (see Kron 1980b).

Photometry of galaxies is not a well-defined procedure and requires attention to many technical details, since a number of systematic errors or biases emerge at very low signal-to-noise ratio: 1. Small errors in the subtracted sky can easily dominate the net photometric errors. 2. Crowding of images becomes a significant problem at faint limits (by $B = 26$, the average separation is only 12 arcsec, with many galaxies overlapping). Software must be able to distinguish cases of confused images and to account properly for the flux in the individual components. 3. Ultraviolet images of nearby spiral galaxies, which will approximate the appearance of faint galaxies in the U and B bands, show distributed patches of high surface brightness (Bohlin et al 1991). Thus real images might not conform to the centrally-concentrated, contiguous idealization of image-detection algorithms. 4. Some effects are peculiar to isophotes in noisy data. Due to photon shot noise, even a centrally concentrated image may break up into small islands that become difficult to reassemble without bias in the derived fluxes. Moreover, objects will appear artificially bright because statistically low pixels will be excluded from the isophotal area. 5. There will be a statistical redistribution of objects resulting in steeper counts because there are more faint galaxies than brighter ones and the photometric errors increase with increasing magnitude. 6. Competing with this effect is increasing incompleteness with increasing magnitude. 7. A different problem is the photometric zero point, which is based on bright stars that have spectral shapes quite different from those of high-redshift galaxies, but this is expected to be a small, second-order effect.

Accurate interpretations of faint galaxy counts should thus be based on detailed simulations of the selection function, random errors, and known systematic errors. We prefer to include these aspects in the model rather than apply correction factors to the data. In this review, we adopt this viewpoint by emphasizing the common elements of observations by independent groups and by plotting uncorrected data.

2.1.2 BRIGHTER GALAXY COUNTS Galaxy counts at $B < 19$ provide the normalization for the faint-galaxy expectations. However, in several respects bright-galaxy photometry is harder than faint-galaxy photometry because the range of surface brightnesses is greater. Also, with the lower surface density of bright galaxies, setting up a spatially uniform photometric system is more difficult, especially with variable Galactic extinction (100 deg^2 must be sampled to get roughly 100 galaxies at $B \sim 15$). Moreover, one needs to correct for the vastly larger number of contaminating stars.

Essentially all modern bright galaxy counts are derived from Schmidt plates, notably the UK Schmidt (see Heydon-Dumbleton et al 1989 and Maddox et al 1990 for examples) and the Palomar/Oschin Schmidt. The counts of Sebok (1986) and Picard (1991) are illustrative of some of the disturbingly large differences between surveys. Both used IIIa-F plates with the Schmidt telescope at Palomar and surveyed contiguous northern regions at $b \sim +50°$. Sebok analyzed four plates, and Picard seven plates. Both made direct calibrations of their photographic photometry with selected galaxies in their fields and reduced their results to the Gunn/Thuan r-band system. The star counts are similar in both studies, yet the galaxy counts, $A(m)$, are apparently different: Over the interval $16.5 < r < 19$, Sebok's counts are steeper than Picard's. At $r = 16.5$, $\Delta \log A = 0.42$, and at $r = 19$, $\Delta \log A = 0.08$, in the sense: Picard (north) − Sebok. The difference between these two northern fields, which are separated by about 60°, is in fact greater than the difference between Picard's northern and southern fields ($\Delta \log A \sim 0.15$). The areas and depths are large enough that the effect of large-scale structure at the level of 1 σ is expected to be less than $\Delta \log A = \pm 0.04$ (S. M. Kent, private communication).

This difference may be partly due to the details of the photometry and its calibration. The measuring machines, the software, the detectors used for calibration, and the technique of calibration, were all quite different. Considering the fundamental limitation of photographic plates to faithfully record intensity levels over a wide dynamic range, the possibility of the data being affected by scattered light in the respective microdensitometers, and the wide range of galaxy profile shapes, even direct calibration of integrated magnitudes on photographic plates may not always be reliable.

Counts of brighter galaxies in the blue band have been studied by many more investigators. The work of Maddox et al (1990) is important because the area covered is 4300 deg^2, far larger than any other photometric survey. Since other surveys lie within the Maddox et al (1990) region, there is the opportunity to compare photometry on a galaxy-by-galaxy basis: Differences in the zero points for each common field are of order 0.15 mag (Maddox et al 1990).

Maddox et al (1990) called attention to the steeper slope of their counts, $\Delta \log A/\Delta m$, in the general range $17 < B < 19$, than predicted by Ellis's (1987) non-evolution model. In fact, the steep slope in this region is characteristic of a number of such studies, e.g. Butcher & Oemler (1985), Stevenson et al (1986), and Heydon-Dumbleton et al (1989). Butcher & Oemler (1985) presented a summary of the Kirshner et al (1978) and Kirshner et al (1983) field-galaxy counts and color distributions. Stevenson et al (1986) presented data from 17 Schmidt fields covering 355 deg^2. Heydon-Dumbleton et al (1989) surveyed 100 deg^2; over 3000 galaxies in their survey are in the interval $17.5 < B < 18.5$. All of these surveys are characterized by a slope that is as steep as that of Maddox et al for $B < 19$. Even more extreme are Sebok's counts, which reach deeper than the blue counts discussed so far, and yet are almost as steep as the Euclidean case $\Delta \log A/\Delta m = 0.6$ up to $r = 18$, where confusion with stars begins to become important. We will return to this result in Section 3.3.

2.1.3 FAINTER GALAXY COUNTS Counts in the U-band have been presented by Koo (1986), Majewski (1988, 1989), Guhathakurta et al (1990b), Songaila et al (1990), and Jones et al (1991). Majewski's (1989) counts suggest a possible flattening fainter than $U \sim 24$—a potentially important result that needs confirmation. Counts in blue and red bands have received the most observational attention, and the current status has been reviewed by Metcalfe et al (1991). I-band counts have been made by Hall & Mackay (1984), Koo (1986), Tyson (1988), Hintzen et al (1991), and Lilly et al (1991). K-band counts have been summarized by Broadhurst et al (1992) and by Cowie et al (1992). The limit of extreme crowding and extremely low signal-to-noise ratio, $B > 26$, has been studied so far only by Tyson (1988) and by Lilly et al (1991).

Figure 1 shows the differential counts log $A(m)$ (number per deg^2 per mag) for surveys in the blue, red, and near-infrared bands, transformed where necessary to the adopted standards of photographic b_J, Gunn r, and K, according to information presented in the original papers. Some differences do appear between different investigators, but the overall agreement is obvious, and we do not distinguish between the separate surveys in Figure 1; sources are given in the figure caption. To prevent excessive

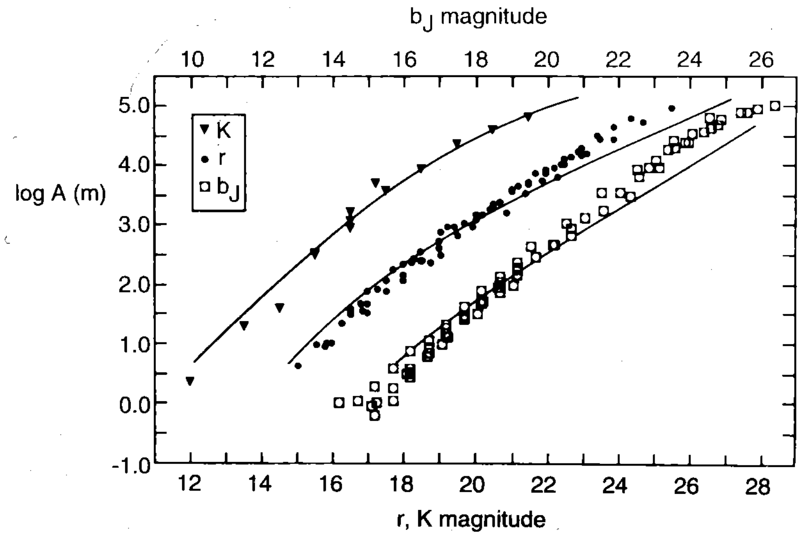

Figure 1 Differential galaxy counts $A(m)$ in number per square degree per magnitude in the blue (b_J), red (Gunn r), and near-infrared (K) bands. The magnitude scale for the b_J counts is at the top. To cover the greatest range in magnitude, the plot shows bright photographic surveys and faint CCD surveys. Sources for the blue counts: Butcher & Oemler (1985), Stevenson et al (1986), Ciardullo (1987), Heydon-Dumbleton et al (1989), Maddox et al (1990), Jones et al (1991), Tyson (1988), Metcalfe et al (1991), Neuschaefer et al 1991, Lilly et al (1991). Sources for the red counts: Stevenson et al (1986), Sebok (1986), Picard (1991), Hall & Mackay (1984), Yee et al (1986), Tyson (1988), Metcalfe et al (1991). Sources for the K-band counts: Mobasher et al (1986), Broadhurst et al (1992), Cowie et al (1992). The curves give the predicted counts for the no-evolution model discussed in the text, all sharing a common normalization.

crowding of the points, in general we have omitted photographic photometry for b_J and r in the intermediate range of magnitudes. We have plotted data only brighter than conservative limits where the statistical noise in the sky background is comparable to the flux itself (and beyond which the corrections for incompleteness become large).

2.2 *Angular Correlation Function*

Another potentially powerful and independent probe of evolution and cosmology is the angular clustering of faint galaxies, since such measures are sensitive to the redshift distribution of the sample and the cosmological model (Peebles 1980). Koo & Szalay (1984), Stevenson et al (1985), Pritchet & Infante (1986), and Jones et al (1988) have measured the two-point angular correlation function to the limit of photographic counts ($B = 23$–24), where the scaled correlation amplitude appears to be the same as found locally. More recently, CCD data have extended the results to $B > 25$ (Neuschaefer et al 1991, Efstathiou et al 1991). Despite the nominal simplicity of the experiment, the various measures of the correlation function at low amplitudes are consistent only within a factor of 2 to 3, and may reflect not only variations in photometric zero points, but also the exact method for calculating the clustering and for correcting the background.

Efstathiou et al (1991) found a low clustering amplitude at 30-arcsec separations, a result that was especially apparent for the bluer galaxies. If there had been extensive galaxy-galaxy interactions at observable redshifts, then the clustering amplitude at short scales might be expected to show an enhancement, rather than the decline seen in the data. Efstathiou et al (1991) prefer a picture in which weakly clustered blue galaxies are apparent at high redshift, but are not observed locally. These and other interpretations of the correlation amplitude in faint data assume that galaxies of differing types and luminosities share the same intrinsic clustering properties. In fact late-type spirals are found typically to have about a factor of 4 lower clustering amplitude than early-type galaxies (Davis & Geller 1976, Giovanelli et al 1986). This dependence should be taken into account, since fainter samples of galaxies are naturally expected to be weighted more towards bluer and lower-luminosity galaxies.

It is preferable to measure *spatial* correlation with complete redshift samples. A pioneering attempt with faint galaxies was made by Loh (1988), who estimated redshifts from multicolor photometry for a sample of 1000 galaxies brighter than $I = 22$ and explored the two-point spatial correlation function to $z = 0.75$. He found no evidence for a change in power-law slope nor convincing changes in the clustering amplitude. We anticipate that the study of clustering evolution will gain prominence as larger samples of spectroscopic redshifts for faint field galaxies are acquired.

2.3 *Colors*

Colors of field galaxies provide the data needed to categorize the mixture of stellar populations and to measure star-formation rates. By adding passbands, one can rapidly increase the number of dimensions for analysis of spectral energy distributions. Although higher precision (typically <0.1 mag in the color) is needed, such data can be efficiently gathered with broadband filters for faint galaxies. With three or more passbands, multicolor photometry measures independently the intrinsic colors and crude redshifts of faint galaxies (Baum 1962, Koo 1985, Loh & Spillar 1986), especially if multiple medium-wide passbands are employed (Couch et al 1983). Extending this technique to large numbers of narrow bands may be practical (Gibson & Hickson 1991).

Measurements of color in a uniform photometric system for statistically complete samples of galaxies brighter than the $B < 15.5$ limit of the Zwicky catalogue are surprisingly few, even for galaxies with measured redshifts. This imbalance is due to the same difficulties encountered by counts of bright galaxies, namely the need for coverage of a large solid angle; the saturation of bright galaxies on photographic plates; and the more complex procedures required to handle contamination by the relatively high surface density of stars.

In the last decade, near-infrared photometry has provided a large extension of the spectral range useful for observations of faint galaxies. The first such study was a $B = 21.5$ sample of 47 field galaxies by Ellis & Allen (1983). This was followed by the larger but brighter sample by Mobasher et al (1986) which was limited at $B = 17$. A K-limited sample can be derived that is complete to about $K < 12.5$ (89 galaxies in this sub-sample). With the advent of near-infrared arrays, K-band fluxes have been measured for faint field galaxies (Elston et al 1990, Bershady et al 1990), even to surface densities similar to those achieved in the optical band (Cowie et al 1990, Cowie et al 1992).

There are additional technical complications from combining two or more magnitudes together. Colors may be measured within a smaller aperture than used for the magnitudes (sometimes within a fixed aperture size) to improve the signal-to-noise ratio. The implicit assumption is that radial color gradients in galaxies are small. Some workers have even combined fluxes measured through different effective apertures, but this is likely to introduce dangerous systematic color variations as a function of magnitude and true color. There is also the complication of deciding how to choose the detection limits in the various bands. Images in each passband may be combined before the photometric procedures are applied to improve the depth of the survey or to provide simultaneous measurement of the magnitudes and colors (Ciardullo 1987). For photometry at very faint levels, fluxes in some bands may even be measured as negative, due to expected sky-subtraction fluctuations. Moreover, unless the photometric errors are very small, color errors are usually asymmetrical and can exhibit complicated shapes in different regions of multicolor diagrams (see Figures 9a or 9c of Koo 1986). Having different incompleteness limits for each passband further complicates the interpretation of such plots.

Many passbands have been used for faint-galaxy work; since published photometry in Kron's (1980a) blue and red bands spans a large range in magnitude, we will adopt this as a common system for this review. For the blue, b_J is defined by the combination of Eastman IIIa-J emulsion and

GG385 filter. For galaxies at $z \sim 0.5$ and with colors typical of spirals, a rough approximation is $b_J = B - 0.3$. For the red, r_F is defined by the Eastman IIIa-F emulsion and GG495 filter, and is photometrically intermediate between V and R.

2.3.1 PHOTOGRAPHIC COLORS $15 < B < 20$ The color distribution of nearby galaxies can be determined from a number of relatively bright surveys. Kirshner et al (1978) measured asymptotic or "total" magnitudes and colors on photographic plates for a sample of 807 field galaxies brighter than $B \sim 16$ in eight fields toward the Galactic caps. A fainter, red-limited sample (to their $F \sim 17$) was subsequently published by Kirshner et al (1983). The results of these two surveys, plus an extension to $B \sim 19$ for field galaxies, have been tabulated in convenient form by Butcher & Oemler (1985) as part of their study of the colors of nearby rich clusters of galaxies (Figure 2). A similar study was made by Couch & Newell (1984), who compiled a large sample of field-galaxy colors as a function of R magnitude.

2.3.2 PHOTOGRAPHIC COLORS $B > 20$ There is extensive multicolor photometry fainter than $B \sim 20$, mostly from prime-focus plates taken with 4-m class telescopes. These plates cover 0.3 to 0.5 deg^2 and typically yield 10,000 galaxies or more per exposure to $B = 24$, with useful colors brighter than $B \sim 23$.

Kron (1980a) showed that the $b_J - r_F$ colors of fainter galaxies become significantly bluer beyond $B \sim 22$. Many faint galaxies were actually bluer than an actively star-forming galaxy like the Large Magellanic Cloud, unless placed at redshifts beyond $z \sim 1$. Shanks et al (1984), Infante et al (1986), and Tyson (1984) confirmed these results. By adding U and I bands, Koo (1986) was able to add two more dimensions to the color analysis and thus resolve the ambiguity between redshifts and intrinsic colors. One new and somewhat unexpected finding was evidence for a substantial increase of intrinsically blue galaxies at redshifts between $z = 0.4$ and 1. This was, however, a model-dependent conclusion that needs spectroscopic redshift confirmation. The colors of some galaxies fainter than $b_J = 23$ are consistent with substantially higher redshifts (see Koo 1990). Koo also found that the slope of the counts depends on the bandpass, such that the slope progressively becomes flatter from the super-Euclidian rise ($\Delta \log A/\Delta m > 0.6$) from $U = 20$ to 22, to shallower values for the redder bands. The photographic work of Jones et al (1991) has largely confirmed these slope changes.

2.3.3 CCD COLORS $B > 20$ With the high sensitivity of CCDs, much fainter limits have become feasible, albeit with only 0.003 to 0.07 deg^2 per frame. Hall & Mackay (1984) published the first such survey, covering a total of

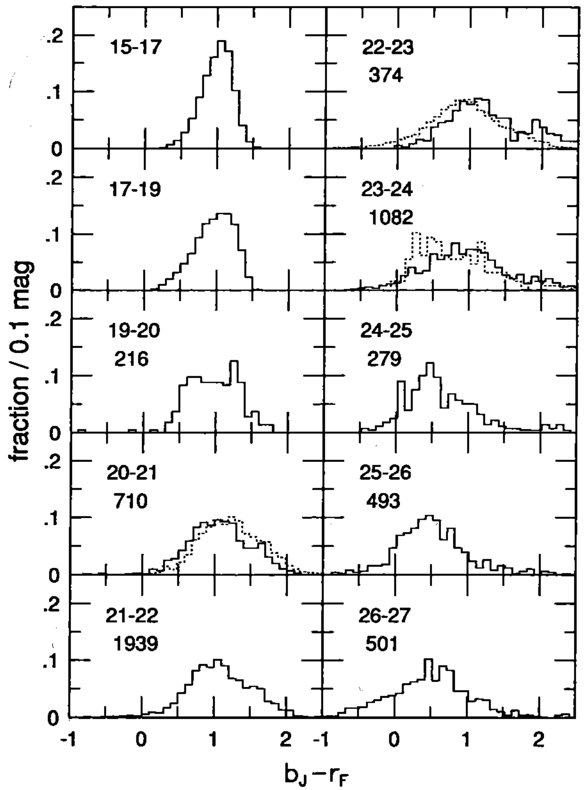

Figure 2 $b_J - r_F$ color histogram for specified b_J magnitudes in bins of 0.1 mag. Numbers give sample size. Left-hand plots are all photographic data, as follows: Butcher & Oemler (1985), the two plots brighter than 19; Kron (1980a), as slightly modified by Koo (1986), for the next three panels. The dotted histogram in the 20–21 panel is from Jones et al (1991), plotted for comparison with the transformation of Metcalfe et al (1991). Right-hand plots are CCD data, with the exception of the dotted histogram in the top panel which extends Kron (1980a) and Koo (1986) another magnitude. From 22 to 24, Metcalfe et al (1991); fainter data are from Guhathakurta (1991) with the $B_J - R$ passbands of Tyson (1988) (no transformation applied). Guhathakurta's data are also shown in the 23–24 panel as a dotted histogram, for comparison. In the faintest panel, non-detections in the R band contribute to the linear drop of the blue tail (P. Guhathakurta, private communication).

50 arcmin^2 to a surface density of 150,000 objects deg^{-2}. They pioneered a scanning technique to achieve excellent flat-fields, and reported that the mean of the $R - I$ colors of their galaxies was essentially constant over their magnitude range, and that the red counts had a relatively flat slope

of $\Delta \log A/\Delta m = 0.4$, confirming the results of the earlier photographic work.

This was followed by the well-known surveys of Tyson & Seitzer (1988) and Tyson (1988), who used three passbands ($B_J RI$) that reached even fainter limits (using a shift-and-add technique that they developed), approaching 500,000 galaxies deg^{-2}. The difference in the slope between the blue and red counts was again seen. Tyson (1988) also noted an "extreme blueing trend in $B_J - R$ color with R magnitude," by more than a magnitude in color over a two-magnitude range in R (his Figure 17). A similar sharp change in the $B-I$ color with increasing I magnitude was reported by Cowie & Lilly (1990), but subsequent work (Lilly et al 1991) shows instead a more gradual trend to bluer colors. Lilly et al (1991) also found mean colors redder than Tyson by ~ 0.8 mag at the faint end. Moreover, the $UB_J RI$ survey of Guhathakurta et al (1990a) found very little change in $B-R$ from $R = 23$ to beyond $R = 26$. The sample of Metcalfe et al (1991) shows blueing of only a few tenths of a magnitude in $B-R$ over a range of 2 magnitudes ($R = 22$ to $R = 24$), but does not reach as faint as these other surveys.

Loh & Spillar (1986) obtained six-band photometry of galaxies in five 0.02 deg^2 fields, complete to $m_{8000} = 22$. They attempted to estimate a redshift for each galaxy based on its apparent low-resolution spectrum, and the derived redshift distribution (E. D. Loh, private communication) is at least qualitatively consistent with the redshift distributions derived spectroscopically, discussed in Section 2.4.

Cowie (1988) suggested the presence of a large fraction of faint galaxies with $z > 2.8$ based on the observed flux at 3400 Å being very faint, presumed to be due to the Lyman-continuum break at 912 Å entering the U band. However, the deep U-band CCD surveys reported by Majewski (1988, 1989), Guhathakurta et al (1990a), and Lilly et al (1991) do not exhibit an unusual proportion of galaxies with red enough $U-B$ colors.

In summary, one of the relatively well-established phenomena of faint galaxy photometry is the gradual trend to bluer mean colors at fainter magnitudes. This is seen in colors comprising a blue band like $U-B$, $B-V$, and $B-I$ (Kron 1980a, Koo 1986, Guhathakurta et al 1990a, Lilly et al 1991, Metcalfe et al 1991), but is not so evident in redder colors like $R-I$ or $R-K$ (Hall & Mackay 1984, Koo 1986, Tyson 1988, Hintzen et al 1991, Elston et al 1990). A possible interpretation is that the proportion of intrinsically blue galaxies fainter than $B = 22$ increases, but the blue galaxy population does not itself become much bluer. It is worth recalling that qualitatively, the trend to bluer colors fainter than approximately $B = 22$ is expected *even in the absence of evolutionary effects* because the K-correction selects against the intrinsically redder and more luminous galaxies and because the color-absolute magnitude relation progressively favors the nearer, bluer galaxies.

2.3.4 "FLAT-SPECTRUM" GALAXIES Some very blue galaxies have spectra that are approximately constant in f_ν over at least a modest range in observed frequency—these are the so-called flat-spectrum galaxies. They are of interest because of their high rates of massive star formation, whatever their redshifts (Cowie et al 1988). Lilly et al (1991) actually adopt $(B-I)_{AB} \leq 0.7$ as a criterion for very blue galaxies, which corresponds to $f_\nu \sim \nu^\alpha$ where $\alpha \sim -1$. The criterion $\alpha > -1$ for very blue galaxies is useful because common subdwarf stars rarely have colors bluer than this. Thus the colors of such stars measured in the same field can then serve as an internal calibration and a check on the size of systematic errors in the photometry. Note that the K-correction including the bandwidth term for a power-law spectral energy distribution is $K(z) = -2.5(1+\alpha)\log(1+z)$, and $\alpha = -1$ conveniently corresponds to zero K-correction.

The $\alpha = -1$ point on a $U-B$, $B-V$ diagram such as that of Huchra (1977; see Matthews & Sandage 1963, appendix) shows that few nearby galaxies are as blue as this (and essentially none are as blue as $\alpha = 0$). Therefore, if such galaxies are seen to appear in the faint (and presumably distant) samples, at face value it would indicate that the redshifts are large enough to bring the expected rise in the rest-frame ultraviolet into the visible band (Code & Welch 1982). Such a claim, however, must be balanced by consideration of the sizes of random and systematic errors in the colors.

The actual colors to be associated with a particular spectral index are not well known, mostly because the stars used to define the photometric system have spectra that are very different from power laws. In attempting to determine the color of $\alpha = -1$ in a particular photometric system, we found that different techniques yielded different values by up to 0.15 mag. Hence, the following quoted fractions of blue galaxies are only rough estimates.

The $(B-I)_{AB}$ versus I_{AB} diagram of Lilly et al (1991) shows that only about 20% of the galaxies in the faintest complete magnitude interval, $23.5 < I_{AB} < 24.5$, are bluer than $(B-I)_{AB} = 0.7$. Unfortunately the number of stars in their small area is too few to allow comparison with the colors of the bluest subdwarfs.

The $R-I$ versus R diagram of Hintzen et al (1991) contains many more objects, but is complete to only $R = 24$. There is a well-defined blue limit to the stars at about $R-I = 0.25$, bluer than which there are fewer than 10% of the galaxies within any magnitude interval. The $\alpha = -1$ color is expected to correspond to about $R-I = 0.43$, and roughly 20% of the galaxies are bluer than this limit.

Similarly, Metcalfe et al (1991) displayed the color distribution of the objects classified as stars, and in this case the blue edge of the stellar distribution does match closely with the $B-R$ color expected for $\alpha = -1$, namely $B-R = 0.70$. The fraction of blue galaxies is at most 15% for the faintest B-selected sample, and much less for the R-selected sample.

We estimate that $\alpha = -1$ corresponds very roughly to $B_J - R = 0.6$ in Tyson's system, which is consistent with the colors of the bluest stars in his survey. His Figure 9 shows $B_J - R$ versus B_J, and approximately half of the galaxies qualify as blue, $\alpha > -1$. The same is apparent in $B_J - R$ versus R (see also Guhathakurta et al 1990a). Earlier we remarked on the sharp trend to bluer colors in Tyson's survey; evidently this trend manifests itself as a population of galaxies that is both bluer and more numerous at a given color than found in the surveys mentioned above.

Color versus near-infrared magnitude diagrams have been presented for K-band selected samples by Elston et al (1990) and by Cowie et al (1992). The former paper shows $R-K$ versus K, and there appears to be a trend to redder colors in the range $14 < K < 18$. Part of this trend is attributable to galaxies at $K > 17$, $R-K > 5$, which the authors suggest are luminous, intrinsically red galaxies with an unusually high space density at $z \sim 1$. The latter paper shows $I-K$ versus K, for which there is no obvious trend of median color with magnitude over the range $16 < K < 22$. The baseline in the colors $R-K$ and $I-K$ is so long that in general there is significant curvature over the sampled spectral range, and the adopted criterion $\alpha > -1$ for blue galaxies is less meaningful.

In summary, the population of faint galaxies with $\alpha > -1$ (or $b_J - r_F < 0.6$ in Figure 2), measured in the visible spectral range, gradually increases and is of order 20% at $B \sim 24$; these are the blue galaxies to which Kron (1980a) originally called attention. Fainter than $B = 24$ the fraction may increase to roughly 50%, but this result needs independent confirmation (cf Lilly et al 1991). The galaxies with $\alpha = 0$ (i.e. the *bona fide* flat-spectrum objects) comprise a much smaller fraction, especially once reasonable allowance is made for random errors in the color measurements.

If the rate of star formation in galaxies was in general substantially higher in galaxies at $z \sim 0.5$, then such an evolutionary effect would be expected to produce a shift towards bluer apparent colors with increasing magnitude. However, there is no strong evidence that these galaxies have especially peculiar luminosities, intrinsic colors, or space densities: In the spectroscopic surveys discussed below, the bluest galaxies at $B > 21$ have been found to have moderate redshifts (Colless et al 1990, Cowie et al 1991). Moreover, because of the color-luminosity relation for field galaxies, the shift to bluer colors is expected even without evolution. The interpretation of the field galaxy color distribution must allow for this effect.

2.4 *Redshift Distributions*

Redshifts are the key measurement required to translate observable magnitudes, colors, and angles into physical luminosities, rest-frame spectral energy distributions, intrinsic sizes, and projected separation distances. Depending on the spectral resolution and signal-to-noise ratio, the spectra used for redshifts may also yield a wealth of additional information on the physical conditions of line-emitting hot gas, limits to the age and metallicity of the component stellar populations, and a measure of mass from velocity widths of spectral features.

The pioneering effort in measuring redshifts of field galaxies faint enough to probe galaxy evolution ($B \sim 20$) was by E. Turner, J. Gunn, and W. Sargent in the late 1970s using the Palomar 5-m telescope and a SIT digital spectrograph. Their sample was selected visually by R. Kron to span a wide range in morphology and surface brightness. Their results were briefly described by Turner (1980) and Gunn (1982), and they generously allowed 58 redshifts to be published by Koo (1985). Since then, a number of fainter, better-defined redshift surveys of field galaxies have been undertaken as detailed in Section 2.4.2.

2.4.1 REDSHIFT SURVEYS $15 < B < 17$ Bright redshift surveys provide a local measure of the luminosity function and other properties of galaxies for comparison to more distant samples. The best known field samples are the large ($N \sim 9000$) optical and 21-cm redshift surveys limited at $B \sim 16$ or $z \sim 0.05$ (Giovanelli & Haynes 1991). Unfortunately, the general lack of good photometric colors; the use of small spectrograph entrance apertures that sample mainly the nuclear regions; the incompleteness of samples based on 21-cm redshifts; and the uncertainties due to effects of large-scale structure, have together restricted the usefulness of many of the brighter redshift surveys for faint galaxy studies. Good measures of magnitude, color, and radial profiles are needed, whereas in practice morphology (which has a poor relationship to color—see Figure 7 of Huchra 1977) and eye-estimated magnitudes from the Zwicky or UGC catalogs are often the main data available. Much more valuable has been the $B \sim 16$ survey of 164 galaxies by Kirshner et al (1978) in eight patches of sky with colors and a well-defined magnitude limit; a similar but fainter study by Kirshner et al (1983) of six fields with 280 redshifts; the $B \sim 17$ survey of 329 galaxies by Peterson et al (1986) in five patches, with photographic blue magnitudes; and 264 galaxies, sampled 1 in 3, in nine patches by Metcalfe et al (1989), also with photographic blue magnitudes. These surveys have been used to compute the field galaxy luminosity function; in addition, the Kirshner et al (1978) and Kirshner et al (1983) surveys have been important for establishing the color dependences, as discussed in Section 2.3.1.

2.4.2 REDSHIFT SURVEYS $B > 17$ Fainter surveys have been made practical with the development of multiple-object spectrographs. Fiber-fed spectrographs (Hill et al 1980, Gray 1986) can be used to survey a wide field of view, and moreover, the formatting of the spectra on the detector can be arranged to take full advantage of the area of the CCD. Since more than 100 spectra can be measured simultaneously, and since CCDs are at least a factor of 5 times more efficient than the previous generation of photo-emissive detectors, thousand-fold gains in observing efficiency have been achieved. The multiple-fiber technique is complemented by placing a mask with multiple slits in the focal plane and reimaging the focal plane through a low-resolution spectrograph. The configuration must be arranged such that the spectra do not overlap. This technique is useful when the surface density of objects is high because the field of view is smaller, and the detector area would otherwise not be used effectively. Since the background sky is sampled locally along a slit passing through each object, better sky-subtraction can be achieved, and the multiple-slit technique is normally used at the faintest flux levels.

Several groups have attempted redshift surveys with hopes of pushing beyond $B = 20$ to $z > 0.2$ where evolution might be detectable. Most well known (and fully published) are the surveys of Broadhurst et al (1988) of 187 galaxy redshifts to $B = 21.7$, and Colless et al (1990) of 87 galaxies to $B = 22.5$. The former group used a multiple optical-fiber system, while the latter group used a mask with multiple slits and a wide-field spectrograph camera. Both surveys are roughly 80% complete. Lilly et al (1991) reported six spectroscopic redshifts to $B \sim 24$, and Cowie et al (1991) have extended this survey to obtain an almost complete sample of 21 redshifts to the same limit. The largest survey is that undertaken at Kitt Peak National Observatory by Koo & Kron (1987) with over 400 redshifts complete for $B < 20$, but less than 50% complete at $B \sim 22$. This sample has yet to be published in detail, but some of the data will be presented for illustration. The Broadhurst et al sample has only blue magnitudes; the Colless et al sample has $B-R$ colors as well; the Koo & Kron surveys have Ub_Jr_FI photographic photometry; the Lilly et al survey has *UBVI* CCD photometry; and the Cowie et al sample has in addition very deep *K*-band photometry.

Figure 3 gives the $b_J - r_F$ colors versus redshift for a subsample of faint galaxies with redshifts and measured colors that can be reliably transformed to our system. The expected red and blue boundaries have

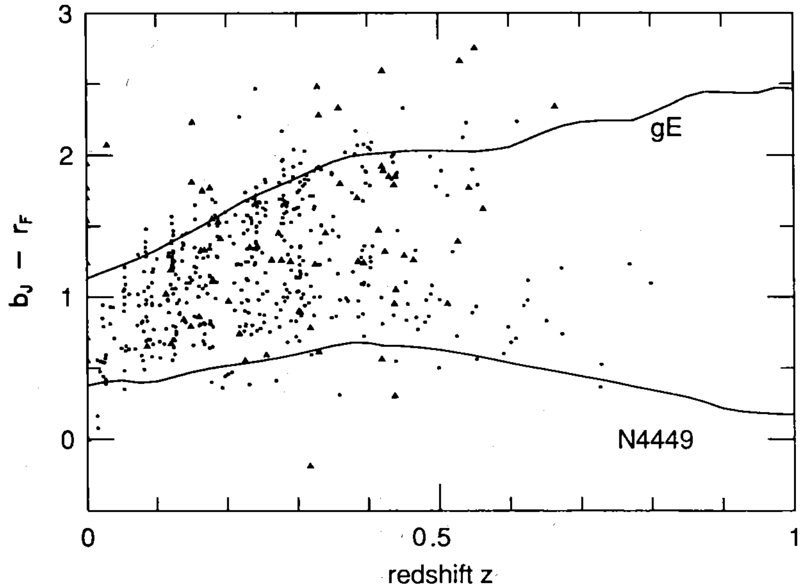

Figure 3 $b_J - r_F$ color of galaxies versus their spectroscopic redshifts. The dots are the authors' data; the triangles are from Colless et al (1990), transformed in color according to Metcalfe et al (1991). The curves show the colors of an average elliptical galaxy (gE) and NGC 4449 (G. Bruzual, private communication).

been derived from redshifting appropriate empirical spectra through the b_J and r_F passbands (these spectra are well matched by the model spectral energy distributions discussed in Section 3.3). In general the data fall within the expected boundaries, but it is noteworthy that, if the colors are accurate, galaxies even bluer than NGC 4449 are present at all redshifts (see also Colless et al 1990). Moreover, field galaxies at $z > 0.5$ can be found that appear similar to local elliptical galaxies, a result consistent with the findings of Oke (1983) and Hamilton (1985), who used the continuum break at 4000 Å instead of colors.

Figure 4 shows the data in the form of redshift versus blue magnitude (the points from Dressler & Gunn 1992 are discussed in Section 2.5). Horizontal bands of points within a given survey reflect large-scale structure along the line of sight. Such structures can be seen in the authors' data at intermediate magnitudes, $18 < B < 20$, even though five separate fields have been combined in this plot. It is evident from the distribution of points in Figure 4 that the average underlying redshift distribution

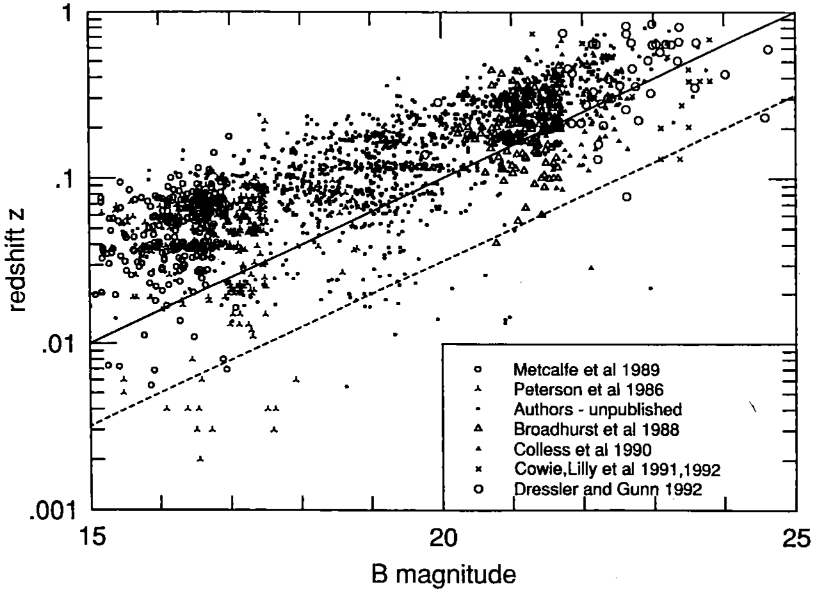

Figure 4 Log redshift versus blue magnitude of major redshift samples with magnitude limits fainter than $B = 16$. Completeness, reliability, and selection effects vary and have not been made homogeneous. The Dressler & Gunn (1992) sample consists of their interlopers, i.e. foreground and background galaxies in their rich cluster fields. The diagonal lines indicate simply the inverse-square law, $B = 5 \log z + 25$ for the solid line, corresponding roughly to 0.1 L^* (the dashed line is drawn for 0.01 L^* to indicate the luminosities of true dwarfs). The lines correspond to $q_0 = 1$ and zero effective K-correction. For a smaller value of q_0 and a K-correction that applies to an average of non-evolving field galaxies, at high redshift the lines bend away from the naive inverse-square law towards fainter magnitudes, like the upper envelope of the distribution of data points.

cannot be accurately derived from samples of even hundreds of galaxies at large distances. As described in the caption, the diagonal lines indicate approximate loci of constant luminosity. It can also be seen that galaxies of quite low luminosity, i.e. true dwarf galaxies, appear at all magnitudes, but in relatively small numbers (cf Cowie et al 1991, 1992).

If field galaxies were overall more luminous at earlier epochs, one would expect the distribution of points in Figure 4 to be shifted progressively to brighter apparent magnitudes at higher redshifts. The early-type galaxies might have been brighter by approximately 0.5 mag at $z = 0.5$ (Tinsley 1972), roughly comparable (but of opposite sign) to the K-correction. The luminosity evolution of the later-type galaxies depends on the unknown

change in the rate of star formation and may well have been less strong. One might conservatively expect that evolution in Figure 4 would be a subtle effect, especially considering the modulation of the data by the large-scale structure.

Figure 5 gives the cumulative redshift distributions for these same surveys, binned in apparent magnitudes as described in the caption. The normalized cumulative redshift distributions are useful in principle because even incomplete samples can be used, *so long as the incompleteness is unbiased in redshift*. Unfortunately, this qualification is expected to be difficult to achieve in practice for $B > 21$, and thus one should be cautious in accepting the $B > 21$ samples in Figure 5 as being representative. A priori we expect a smooth dependence on magnitude of the separate cumulative redshift distributions. Luminosity evolution may manifest itself as a relatively subtle change in the shape of the high-redshift tails, and the change should be smoothly progressive between intervals of apparent magnitude. On this basis, it seems likely that the faintest bin, $B > 23$, is incomplete at high redshifts.

Broadhurst et al (1988) have argued that since the median redshift matches their no-evolution model while the observed counts are too steep, evolution in the *shape* of the luminosity function is required, a conclusion that was echoed by Colless et al (1990). Galaxies that are currently of lower luminosity may have experienced more frequent bursts of star formation at the relevant redshifts, $z > 0.1$. This argument was supported by co-adding in the rest frame the spectra of six galaxies with relatively strong W_{3727}. The mean spectrum showed strong Balmer lines in absorption and a blue continuum, indicative of an episode of recent star formation. This is a promising technique, and with additional data it will be possible to look for correlations of Balmer aborption-line strength with absolute magnitude and with redshift.

The evolutionary picture of Broadhurst et al (1988) and Colless et al (1990) is however not unique, as Guiderdoni & Rocca-Volmerange (1990) have been able to account for the data without such luminosity-dependent luminosity evolution. We shall return to the interpretation of the redshift distributions later, but stress a number of cautionary points for accepting these faint redshift surveys as necessarily being representative. Of most importance is the possible bias against higher redshift galaxies, since these are expected from surface brightness considerations (Section 1) to be the most difficult to measure at a given magnitude (unless evolutionary effects compensate). The missing galaxies are most likely to be exactly those of most interest for tests of evolution or cosmology. Thus far, not a single galaxy with $z > 1$ has been spectroscopically measured with high reliability in the above surveys (but see the next section on samples selected in other

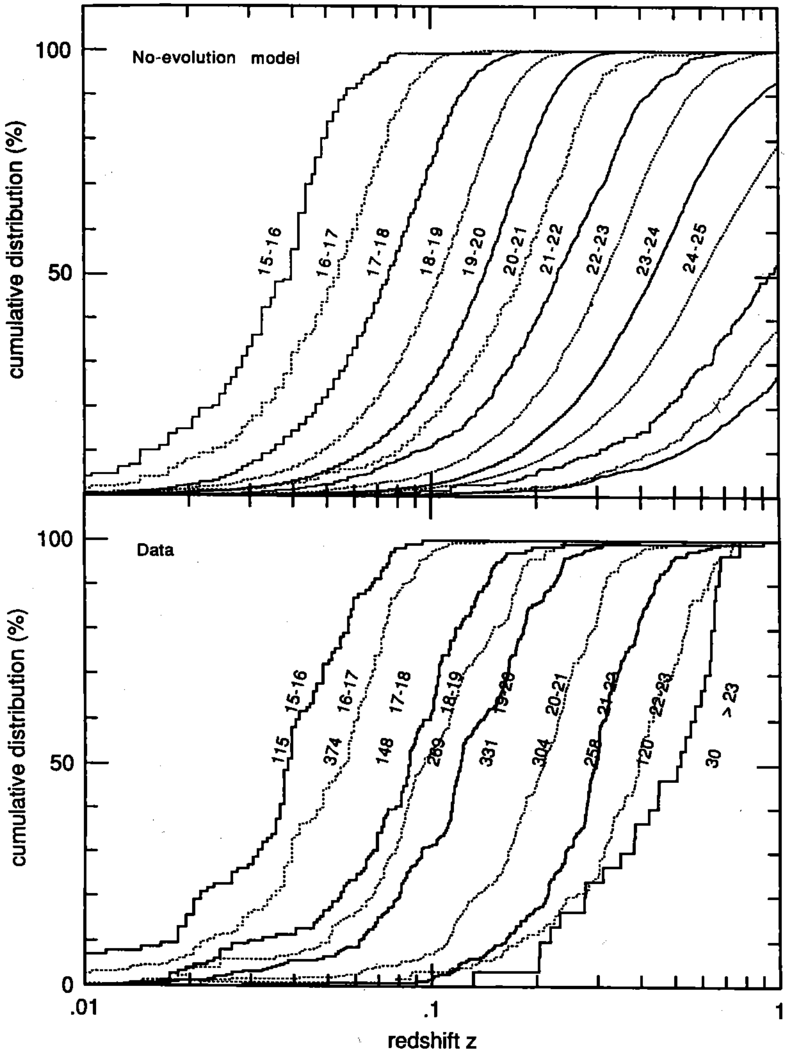

Figure 5 Cumulative distribution functions versus redshift for samples binned in steps of one magnitude. The top panel gives the homogeneous no-evolution model discussed in the text, and the bottom panel is derived from Figure 4 as follows. The number of galaxies contributing to each magnitude bin is indicated. The leftmost curve is for $B = 15$–16 (*thicker solid line*), the next $B = 16$–17 (*thinner dotted line*), and so on as indicated. The brightest two bins were derived from Peterson et al (1986) and Metcalfe et al (1989); the next three bins, to $B = 20$, are from the authors; the following bin ($B = 20$–21) includes both the Broadhurst et al (1988) sample and that of the authors; $B = 21$–22 includes those two samples and that of Colless et al (1990); $B = 22$–23 and $B > 23$ are from Colless et al (1990), the authors, Cowie et al (1991), and Dressler & Gunn (1992).

ways). Unless this failure is due to a true lack of such galaxies in the samples, it may only reflect the unfortunate circumstance that at high redshifts, strong spectral features like the 4000 Å continuum break move into the very noisy red portion of the sky. For emission-line galaxies, only the [O II] 3727 doublet is visible at redshifts $z \sim 0.5$ when the redder set of confirming emission lines, Hβ and [O III] 5007, move into the red.

Independent samples can, however, be compared over similar magnitude ranges to check the completeness and to examine the distribution of the high redshift tail. It is possible that there has indeed been a systematic loss of high redshifts among the Broadhurst et al (1988) and Colless et al (1990) samples. The fainter portion of the Broadhurst et al (1988) sample is relatively less complete but happens to overlap the bright and virtually complete portion of the Colless et al (1990) sample between $b_J = 21$ and 21.7. Using the Kolmogorov-Smirnov test, we find, in this overlapping magnitude range, less than a 1% chance that the two distributions were drawn from the same parent population, with the more complete Colless et al sample showing a more extended high-redshift tail (23% with $z > 0.4$, versus 4% for the less complete Broadhurst et al sample).

As for the Colless et al (1990) sample, one would expect a larger number of dimmer or weaker-emission-lined galaxies at $z > 0.6$ than are observed. Their incompleteness has recently been decreased from 19% to 5%, yet this paucity of high-redshift galaxies persists (R. S. Ellis, private communication). However, the galaxies selected for the redshift survey show an apparent deficit at the faint end, $22.2 < B < 22.5$, of about a factor of two with respect to the expected count distribution. Another problem pointed out by Colless et al (1990) is that one of their three fields differs from the other two by having a higher redshift tail which was attributed to clustering. Moreover, for a sample of only eight galaxies in the same magnitude range, $B = 21$ to 22.5, Cowie et al (1991) find one at $z = 0.735$ (with broad emission lines indicative of a Seyfert-like spectrum), another at $z = 0.644$, and one at $z = 0.479$. The published sample of Colless et al (1990) is 11 times larger, but has only two galaxies with $z > 0.6$, and only 15 galaxies with $z > 0.45$. The various strong selection effects mentioned earlier must be better understood, and the surveys must reach a greater level of self-consistency, before more conventional expectations for the galaxy redshift distribution, such as a slight increase in the fraction of higher redshift galaxies due to luminosity evolution in the bulge populations, can be rejected with confidence.

Apart from the issues of incompleteness just discussed, the distribution of redshifts within an interval of apparent magnitude, and in particular the median redshift, is a more problematic test for evolution than it might first seem. The low end of the redshift distribution at a fixed apparent magnitude contains information only about the faint end of the luminosity function, and is particularly susceptible to the effects of large-scale structure because the volume sampled is small. On the other hand, the high-redshift end of the distribution contains information not only about the bright end of the luminosity function, but also about the volume element, the overall effective K-correction, and galaxy evolution. Tests for evolution that compare data such as Figure 4 with a model for the redshift distribution should weight high redshifts more than low redshifts, because the unweighted median may be affected by irrelevant uncertainties at low redshift.

2.5 *Other Samples of Galaxy Redshifts*

The redshift surveys just discussed (i.e. magnitude-limited samples of field galaxies) have so far failed to reveal a significant population of galaxies at $z > 0.8$. Nevertheless, such galaxies are known to exist based on other kinds of discovery techniques (including serendipitous discoveries). In some cases the high-redshift galaxies would have met the criteria for selection by the field-galaxy surveys and can therefore be regarded as "normal." However, for galaxies that were not found in a magnitude-limited sample, it is not straightforward to assess the constraints on evolution because the selection criteria are usually not simply defined. Still, the growing number of plausibly normal field galaxies at $z > 1$ show that at least some galaxies were luminous many Gyr ago, consistent with an early phase of enhanced star formation in massive systems.

To give an impression of the number and nature of the known high-redshift galaxies, in the following several paragraphs we relate examples of the discoveries. We also review other kinds of selection criteria, for example searches for line emission, and what the limits from such surveys tell us about the redshift distribution, and therefore evolution, at very faint magnitudes.

The spectrum from a long slit that was positioned over a quasar yielded an apparently normal galaxy at $z = 1.018$ and $B \sim 24$ (Thompson & Djorgovski 1991). Other galaxies with redshifts of 0.72 and 0.92 have also been found accidentally with long-slit observations (H. Spinrad, private communication).

High-redshift galaxies may be identified as companions to quasars. In their first attempt with a narrow-band filter tuned to the Lyman α line of a quasar, Djorgovski et al (1985) discovered a companion at $z = 3.22$. Heckman et al (1991a,b) and Hu et al (1991) have reported finding several such candidates among radio-bright quasars. They also detected image extension that is perhaps associated with the host galaxy of the active nucleus. Another case which was originally found by broadband imaging is a companion to Q1548+0917 with $z = 2.76$ and $R \sim 23$ (Steidel et al 1991).

Still another method of finding high-redshift galaxies is statistical and relies on using the excess number of objects found around distant quasars. In one early study, Tyson (1986) used a wide R band and found an excess of companion galaxies to quasars at $z = 0.9$–1.5 at a relatively bright limit of $R = 21$, thus requiring a surprisingly large amount (2 to 3 magnitudes) of luminosity brightening at these redshifts. Yee & Green (1987) also reported luminosity brightening, but for cluster galaxies surrounding radio-loud quasars at $z \lesssim 0.6$. Hintzen et al (1991) found an excess of galaxies in the angular vicinity of quasars at $z = 0.9$–1.5, but only by going deeper, to $R = 23$. Even if high-redshift quasars do show nearby companion galaxies, the effect of ionization by the quasars may complicate any interpretation of these galaxies as being normal.

Another powerful technique is to search for galaxies associated with intervening absorption lines seen in the quasar spectra, especially the strong resonance lines of Mg II or damped Lyman α, resulting from the halos or disks of ordinary galaxies. Searching for galaxies at $z > 0.4$ via Mg II absorbers has great promise, as evidenced by the large number of emission-line candidates in the surveys of Yanny et al (1990), Yanny (1990), and Bergeron & Boisse (1991), with one galaxy having been found at $z = 1.025$ (Bergeron 1991). Damped Lyman α searches at significantly higher redshifts ($z > 1.8$) have been less successful (e.g. Smith et al 1989). A few recent candidates lend some encouragement however, at $z = 2.466$ (Wolfe et al 1992), $z = 1.998$ (Elston et al 1991), $z = 2.309$ (Lowenthal et al 1991), and the most distant at $z = 3.409$ (Turnshek et al 1991). The inferred rates of star formation are quite low ($< 10\ M_{\odot}$/year; Smith et al 1989), and the continuum of the galaxy underlying the ionized gas may be extremely faint ($m_{AB} \sim 28$; Wolfe et al 1992).

Galaxies undergoing their initial collapse and star formation may be recognized from strong Lyman α emission or a substantial Lyman-continuum break, and the surveys described above are sensitive to such objects. Pritchet & Hartwick (1987) used narrow-band (100 Å) imaging to detect Lyman α emission in the red, and later Pritchet & Hartwick (1990) conducted a similar narrow-band search but at shorter wavelengths for sensitivity at $z \sim 1.9$. Both surveys yielded only upper limits to the surface density of Lyman α emitters. Lowenthal et al (1990) made a long-slit search of "blank sky" for Lyman α between $z = 2.7$ and 4.7, also without a detection. Evidently galaxies form such that Lyman α is rarely emitted at the luminosities to which these surveys are sensitive, or else the phase of bright Lyman α is at still higher redshifts.

Surveys of distant clusters may yield sizable samples of interloper field galaxies. Most noteworthy is the recent investigation of seven clusters with redshifts between 0.35 and 0.55 by Dressler & Gunn (1992), in which 51 field galaxies with good quality redshifts up to 0.85 were observed (Figure 4). This survey contains some of the faintest and highest-redshift field galaxies known. Dressler & Gunn (1992) applied color criteria because of their primary interest in the properties of the members of the high-redshift clusters, and it is therefore difficult to apply their results to field galaxies in general.

Finally, the large masses of distant clusters can be used as gravitational telescopes to magnify background galaxies (Tyson 1990). The distortions can increase the apparent size of such galaxies and thus amplify their total flux (surface brightness is conserved by lensing). Moreover, elongation of the images results in arc-like structures that are relatively easy to recognize. Redshifts for some of the arcs have been measured spectroscopically (Mellier et al 1991) and range from $z = 0.73$ to a possible 2.24. Despite very long exposures on large telescopes (e.g. 6 hours on Cl 0024+16 with the ESO 3.6-m telescope by Mellier et al 1991), convincing redshifts have not yet been measured for other arcs. Continued surveys for the detection of arcs and subsequent spectroscopy will be completed to fainter surface brightness limits, and the potential of using arcs to obtain a sample of galaxies at $z > 1$ may yet be fulfilled. Even without spectroscopic redshifts, the spatial distribution of lensed galaxies may place limits on their redshifts statistically (Tyson et al 1990).

The future development of these various techniques will identify larger and better-defined samples of high-redshift galaxies. The spectroscopic study of these galaxies will help constrain models for galaxy evolution, especially if the selection effects can be understood in detail. For the moment, the redshift distribution at, say, $B = 26$ is still very much unknown and poorly constrained.

2.6 *Statistics of Emission Lines in Galaxies*

The emission line [O II] 3727 is present in regions of active star formation and appears commonly in the integrated spectra of galaxies (indeed, redshifts for faint galaxies are often based solely on a single line attributed to [O II] 3727, e.g. Minkowski 1961). Unlike Hα which is redshifted into the forest of bright OH sky lines, [O II] remains in a good spectral region up to $z \sim 0.8$. Since emission lines are relatively easy to detect, a measure of the frequency with which this line appears above some specified strength, as a function of redshift, is a natural relationship to explore. Such a test for evolution is in the same category as the distribution of broadband colors as a function of redshift, except that since the strength of [O II] 3727 depends on the excitation and the oxygen abundance, it is a less direct measure of current star formation.

The statistics of [O II] emission at $z_{med} \sim 0.2$ were discussed by Broadhurst, Ellis, and Shanks (1988, hereafter BES), who used these data to support their picture for enhanced bursts of star formation at $z > 0.1$ that were preferentially in galaxies of lower luminosity. Specifically, they found twice as high a fraction of galaxies with an equivalent width of [O II] 3727 (W_{3727}) greater than 20 Å as they would have expected had there been no evolution. This result was reconsidered by Colless et al (1990) in the deeper sampling of the Low Dispersion Survey Spectrograph (LDSS) survey. Colless et al found an excess of only about 40% of galaxies with strong W_{3727}. In both cases the comparison was with respect to the scaled statistics of the $B \sim 17$ sample of Peterson et al (1986). These results were amplified by Broadhurst et al (1992) who showed W_{3727} versus magnitude for all of these surveys, plus a new survey that fills in the gap $18 < B < 20$ (Figure 2 of Broadhurst et al 1992). This diagram shows that within each of the magnitude-limited surveys, the median W_{3727} increases with apparent B magnitude. Taking the surveys together, there is no trend from $B = 16$ to $B = 19.5$, and no trend from $B = 19.5$ to $B = 22.5$. In the regions of overlap the deeper survey of each pair has lower median W_{3727}. The fainter galaxies will naturally have greater random errors in W_{3727}, and it is possible that some of the effect may be due to an asymmetry in the measurement error.

Comparing histograms of W_{3727} for different magnitude-limited samples cannot provide a compelling case for evolution without some check that the samples contain galaxies that are otherwise similar. In fact, if W_{3727} is plotted against redshift, a very different picture is apparent (Figure 6). In the BES sample, there is in fact an *anti-correlation* with redshift, such that galaxies at $z \sim 0.15$ have stronger W_{3727} than galaxies at $z \sim 0.3$. This behavior can be understood if lower-luminosity galaxies tend to have larger W_{3727}, since in the BES sample the narrow range of apparent magnitude results in a strong correlation between redshift and absolute magnitude. In the same way, a dependence of W_{3727} on absolute magnitude would explain why there is an increase in median W_{3727} with apparent magnitude, since in these surveys the apparently fainter galaxies tend to be of lower luminosity.

That lower-luminosity galaxies might have larger W_{3727} is plausible on the basis of the tendency of lower-luminosity galaxies to have bluer $U-B$ colors (Huchra 1977). Although Huchra's (1977) sample of Markarian galaxies included by definition predominantly blue galaxies, the trends of W_{5007} versus M_B and $U-B$ in his sample are likely to be qualitatively relevant. Figure 7 shows W_{5007} versus M_B, indicating that there is indeed a strong correlation between these quantities in the sense needed to explain the BES result.

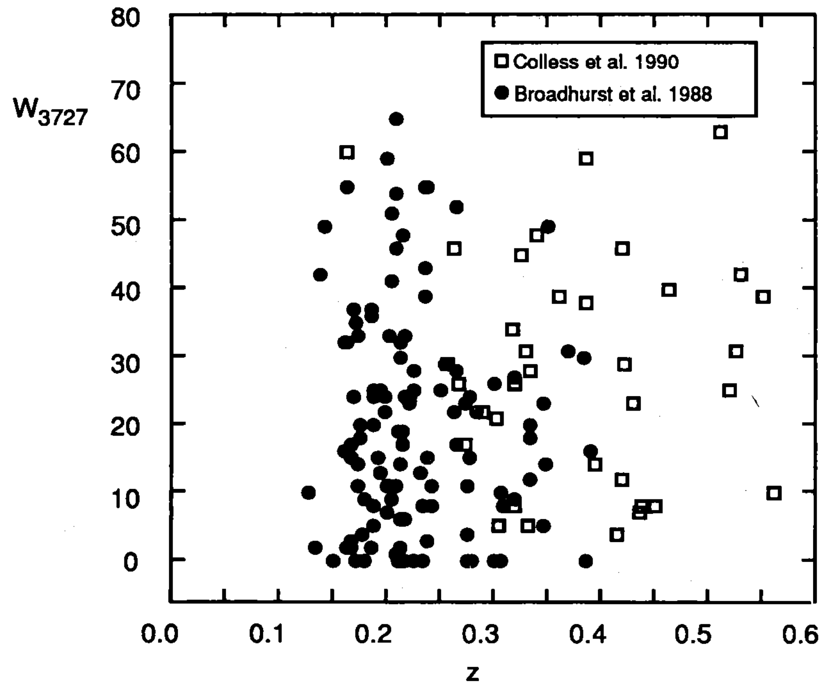

Figure 6 Equivalent width of [O II] 3727 versus redshift for the field galaxy samples of Broadhurst et al (1988) and Colless et al (1990). To ensure that galaxies of similar luminosity are represented at each redshift, only galaxies satisfying $-19.0 < B - 5\log z - 43.9 < -20.5$ have been plotted, which is why there are so few galaxies with $z < 0.15$. Broadhurst et al (1988) report nondetections of [O II] 3727 (the zero values in the figure), but for Colless et al (1990) the lack of a recorded measurement may or may not mean that the line has $W_{3727} = 0$. Hence as plotted the Colless et al data are biased with respect to the Broadhurst data.

Dressler & Gunn (1982) published W_{3727} for 21 nearby field galaxies and showed that for even the bluest galaxies W_{3727} did not exceed 30 Å. This result has been used by others to argue that the high fraction of strong-lined galaxies in faint samples is unexpected and therefore indicative of evolution. There was, however, no effort by Dressler & Gunn to ensure that their sample was *representative* of field galaxies. On the contrary, they state that "the sample was heavily weighted toward Sb and Sc galaxies, since it was realized that these were the only luminous galaxies to have colors much bluer than ellipticals."

In summary, the Broadhurst, Ellis, and Shanks (1988) argument for the

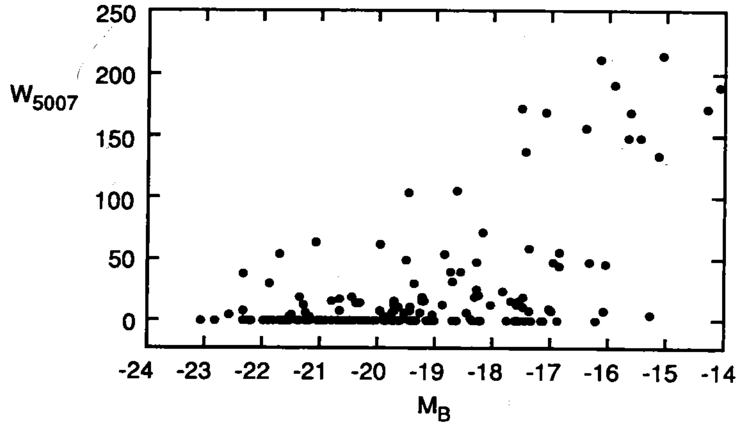

Figure 7 Estimates of the [O III] 5007 equivalent width versus M_B ($H_0 = 50$ km sec^{-1} Mpc^{-1}) from Huchra's (1977) survey of Markarian galaxies. (The distribution of equivalent widths of Hβ, also measured by Huchra, is qualitatively similar.)

increasing prevalence of bursts of star formation at $z > 0.1$ is based partly on the claim that $W_{3727} > 20$ Å is uncommon in local samples, but we have argued that it has not been shown that local samples have been selected in the same way and contain comparable galaxies. Direct evidence in the form of showing an increase in median W_{3727} as a function of redshift is lacking, if one discounts the median W_{3727} at $z \sim 0$. Figure 6 shows W_{3727} for both the BES and the LDSS as a function of redshift, with only galaxies in the range $-19 < M_B < -20.5$ being plotted in order to ensure that the galaxies are comparable, and no trend is apparent. (Had a fainter luminosity interval been chosen, there would have been more galaxies of higher line strength, but the range of redshifts would not have extended as high.)

3. MODELS

There are two distinct kinds of models that are needed to interpret results from faint-galaxy surveys. The first is a model for the statistical properties of galaxies—the relative numbers of galaxies with certain profile shapes, surface brightnesses, and spectral energy distributions—and how a population of galaxies with these properties appears at high redshift. Cosmological effects, effects of galaxy evolution, and clustering characteristics are included in the model.

The other kind of model pertains to the details of the detection process. As remarked earlier, this is an important consideration because at very low detection levels various kinds of systematic errors can predominate. The detection model takes into account the noise from the night sky background, the residual flat-field errors, the effect of seeing, and the operation of a specific algorithm for measuring image fluxes and sizes on such data. A direct way to address these issues is to make an explicit two-dimensional simulation of the sky (Chokshi & Wright 1988), including sources of noise and other image degradation (Yee 1991), examples of which are shown in Figure 8. The same image-reduction methods used on the real sky (examples also shown in Figure 8) may then be applied to the artificial sky to reveal and calibrate the sources of bias. Because of the specific nature of the detection model for each set of observations, we will not discuss the models in depth, but Figure 8 provides examples of the state-of-the-art in simulated images of the sky.

3.1 *Evolution of Stellar Populations in Galaxies*

Attempts to model the changes in the integrated properties of evolving stellar populations—their luminosities and intrinsic colors—have been made by Tinsley (1972), Bruzual (1983), Arimoto & Yoshii (1986), Rocca-Volmerange & Guiderdoni (1988), and subsequent papers by the same authors based on similar premises. The main adjustable ingredients are the shape of the initial stellar mass function and the time history of the rate of star formation. The characteristics of late stages of stellar evolution are in practice also adjustable, but are more explicitly subject to known astrophysical constraints. Some models have included effects of chemical evolution or internal extinction by dust (Wang 1991).

Such models are powerful tools for the interpretation of data, as they allow one to explore quantitatively some of the possible behavior of high-redshift galaxies. However, since the initial mass function and the time history of the rate of star formation are still poorly constrained by independent data or by astrophysical arguments, none of the models should be taken too seriously in terms of predictive power. The shape of the initial stellar mass function is conventionally taken to be that of the solar neighborhood. Although such an assumption does not lead to immediate contradictions when applied to field galaxy samples, its adoption is by default. Similarly, the history of the star formation rate is modeled as some function of the amount of gas available to form new stars; this is not unreasonable, and it is computationally convenient, but none of the formulations has a compelling physical basis.

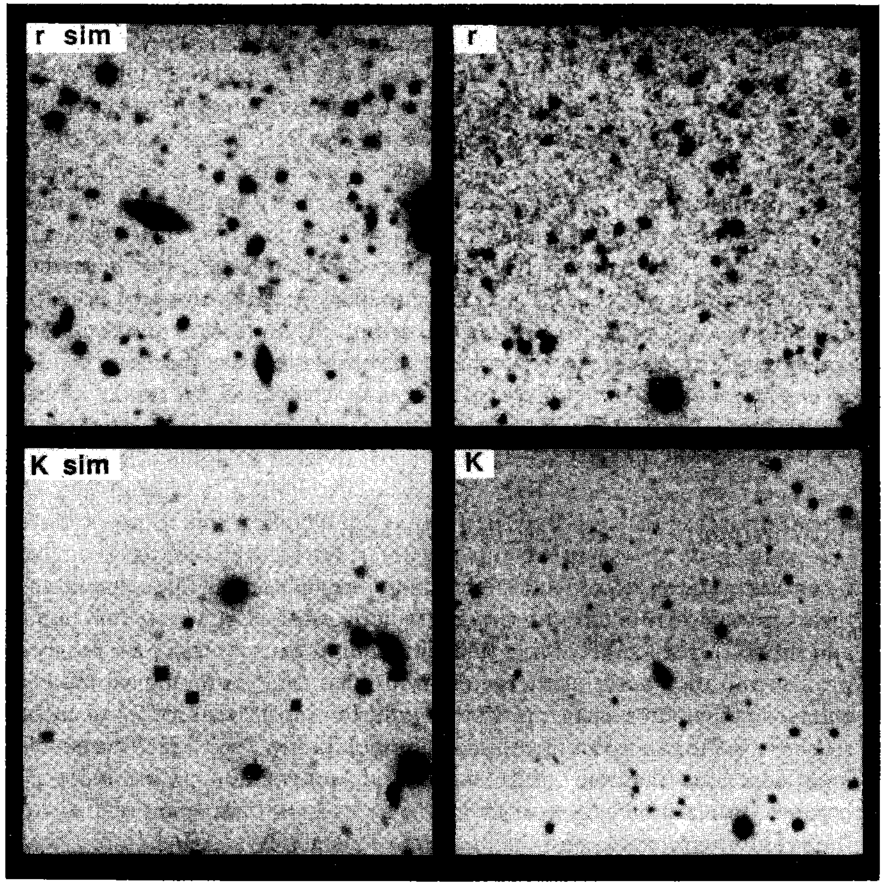

Figure 8 Examples of faint-galaxy fields and simulations, each 96 arcsec on a side. The upper left panel gives a simulated picture for high Galactic latitudes in the Gunn *r* band by Howard Yee (see Yee 1991). It assumes 15,000 sec exposure on a 4-m telescope with 15% overall efficiency, a sky brightness of $\mu_r = 21.4$ mag arcsec^{-2}, 0.4 arcsec pixels, and seeing FWHM = 1 arcsec. The upper-right panel labeled "r" is actually the KG3 filter of Hall & Mackay (1984) for their exposure of Selected Area 57 (also with 0.4 arcsec pixels) with an integration time of 4200 sec on the Kitt Peak 4-m telescope. The lower-left panel is a simulation by Arati Chokshi in Cowie's *K'* band (see Chokshi & Wright 1988). The simulation assumes $\Omega = 1$, an exposure time of 10^5 sec with a 2.2-m telescope, an overall efficiency of 10%, $\mu_K = 14.0$ mag arcsec^{-2}, and 0.48 arcsec pixels. Seeing is roughly simulated with 2 pixels smoothing. The lower-right panel gives the comparison very deep *K'*-band exposure by Cowie et al (1992) of SSA-22, comprising a total exposure of 1.4×10^5 sec.

The amount of blue light (or far-infrared flux) from nearby galaxies is a measure of the young population, but the rate of star formation in the same galaxies billions of years earlier cannot be reliably determined by extrapolation in time. The metallicity, mass-to-light ratio, and gas-mass to total-mass ratio at the present epoch do impose important boundary conditions on the past history of star formation, but the prevailing large uncertainty in galaxy ages illustrates that these boundary conditions do not provide stringent constraints, nor lead to a unique solution for the past history of star formation.

Since one can adjust the redshift of formation and other critical parameters relating to galaxy ages, and since there is freedom to make adjustments in the mix of spectral energy distributions so long as the present-epoch color distribution is reproduced, a rather extensive palette is available to the modeler. One can learn for example which of the model input parameters is likely to be of greatest importance, but the significance of a model fit is often difficult to establish.

3.2 *Magnitude and Redshift Distributions*

Counts of galaxies as a function of apparent magnitude, $A(m)$, depend on the cosmological model, clustering characteristics, the luminosity function, and the mixture of galaxy types (meaning their intrinsic surface brightness profiles and their spectral energy distributions). The cosmological model enters via the volume element dV/dz and the luminosity distance d_L at each redshift. If the evolution of the stellar population is specified in terms of look-back time, then the cosmological model enters in an additional way because it determines the conversion between look-back time, related to the evolutionary clock, and the measured redshift.

For a given apparent surface brightness, different physical radii are reached for galaxies at different redshifts. At high redshifts especially, the fraction of the light seen above the threshold set by the observations may be very sensitive to observational details, such as the degree of image blur from seeing and other sources, depending on the shape of the intrinsic profile for each galaxy (Pritchet & Kline 1981). For this reason, it is of critical importance in a galaxy-count model to know the frequency distribution of galaxy intrinsic profile types. Since the visibility of distant galaxies depends on image profile and the spectral energy distribution, ideally a more general statistical distribution function than the luminosity function $\Phi(M)$ should be used, say $\Psi(M, \mathit{color}, \mathit{surface\ brightness})$. Unfortunately, catalogues of nearby galaxies suitable for deriving Ψ do not yet exist. The alternative is to adopt different functions for $\Phi(M)$ according to galaxy type.

3.2.1 SPECTRAL ENERGY DISTRIBUTIONS Knowledge of galaxy spectral energy distributions allows computation of their *K*-corrections, and ultimately of their redshifts. The mix of spectral types can be usefully considered a function of a single rest-frame color, since galaxy colors tend to be well correlated with each other. However, most models compute the space density as a function of morphological type instead of color, because of the availability of such data. This practice is unfortunate in a number of regards: the difficulty in assigning a meaningful average color to a morphological type, the imperfect agreement between the distributions of types for independent samples (or even between independent classifications for the same galaxy), and uncertainties inherent in the morphological classification procedure.

Most galaxy count models use only five or six galaxy types. This coarse grid of spectra can be traced back to Wells's (1972) large-aperture spectrophotometry of field galaxies. This set of data allowed *K*-corrections and colors as a function of redshift to be computed, for similar galaxies, once the spectra were suitably extrapolated to shorter and longer wavelengths (Wells's spectra covered only the range $\lambda\lambda$3500–5500). These spectra were first used by Brown & Tinsley (1974) and Pence (1976), and later by Coleman et al (1980) and Tinsley (1980). Subsequent models have followed implicitly the same procedure, for instance King & Ellis (1985), Guiderdoni & Rocca-Volmerange (1990), Yoshii & Peterson (1991), and Cole et al (1992).

It is sobering to consider the foundations of this work. Large-aperture spectrophotometry of luminous elliptical galaxies had already been made by Schild & Oke (1971), and it was known that the galaxies contributing to faint counts would be mainly spirals. Wells was able to observe only seven spiral galaxies. These fell naturally into three groups of similar spectra, which were then averaged. These mean spectra could be characterized by the respective mean colors, but have been more commonly labelled by nominal morphological type "Sdm-Im," "Sbc," and "Sab." A class called "Scd" was *invented* by Pence (1976) by interpolation between "Sdm-Im" and "Sbc" and has been adopted by others (e.g. Coleman et al 1980).

The bluest categories are of particular interest because of the anticipation that such galaxies may appear in greater proportions at high redshifts, since their *K*-corrections are smaller. Pence's (1976) bluest class ("Im") contains NGC 1140 and NGC 145. NGC 1140 is called *Sb pec*: in the *Revised Shapley Ames Catalog* (Sandage & Tammann 1981), it appears on the Palomar Sky Survey to have high surface brightness, and on the RSA system has $M_B = -20.4$. NGC 145 is listed in the Arp (1966) atlas (No. 019) and is a striking, high-surface-brightness spiral; it has

$M_B = -21.5$. Neither galaxy bears any resemblance to Magellanic irregulars. Coleman et al (1980) chose not to use NGC 145 in their mean spectra because it was not sufficiently blue for their bluest class. In fact, in their list only NGC 4449 is bluer in $(B-V)_T^0$, by only 0.01 mag. The next-bluest galaxy measured by Wells is NGC 1659, which has $M_B = -22.1$. Thus the galaxies in Wells's list, and the galaxies observed in the ultraviolet by Coleman et al (1980), are for the most part quite luminous systems. NGC 4449 at $M_B = -18.8$ is the least luminous galaxy in either of these lists. Since there is a trend for lower-luminosity galaxies to be bluer (Huchra 1977), the complete lack of low-luminosity galaxies in the library of galaxy spectral energy distributions is an important limitation.

In summary, the models ultimately based on Wells's spectrophotometry suffer from several shortcomings: the galaxies used to define the classes are few and do not properly span the range of colors or luminosities; the blue galaxies do not represent their designated morphological types (and even if they did, the calculation of the numbers of such galaxies per cubic megaparsec would be problematic); it seems likely that there is a selection bias in the spectrophotometric samples in favor of high-surface-brightness galaxies; and it has not been demonstrated that the galaxies are representative of either magnitude-limited or volume-limited samples.

3.3 *A Conventional Model to Fit the Observations*

We have constructed a new model for faint galaxy statistics to evaluate some of the claims described earlier concerning the distribution of counts, colors, and redshifts. In particular, this model allows us to evaluate the faint K-band counts on the same basis as the counts at shorter wavelengths. The galaxy spectral energy distributions are those of Bruzual (1988 version of the models), and are basically similar to those of Guiderdoni & Rocca-Volmerange (1987). The modeling procedure is elaborated in Bruzual (1988, 1990), except that we now constrain the model with the observed redshifts (Figure 5).

We adjust the intrinsic colors and luminosities to match bright-galaxy data. Valuable guides in this work have been the (K, $B-K$, z) distribution of a sample of bright galaxies by Mobasher et al (1986), and the luminosity function parameters suggested by Shanks (1990; see also Metcalfe et al 1991) according to categories of rest frame $B-V$. An important spectral energy distribution is that which results from a constant rate of star formation and a Salpeter initial mass function (which can be thought of as a kind of "default" model galaxy). It has $B-V = 0.56$ at the present time, and the adopted luminosity function corresponding to this spectral energy distribution has a steep slope ($\alpha = -1.5$ in the Schechter formulation) to fainter luminosities. Bluer galaxies, which are essential to match both the bright and faint color distributions, are modeled as having also a constant star formation rate, but with a mass function that is relatively enhanced in massive stars. Five such components were added to reproduce at least qualitatively the color-luminosity relations of Huchra (1977) and Bershady et al (1990), i.e. the bluest galaxies appear selectively at the lowest luminosities. Redder galaxies at the present epoch are the "μ-models" of Bruzual (1983) with a flat luminosity function ($\alpha = -1$) at faint luminosities. Four such components were added to reproduce the redder galaxies; as expected, these are especially important in modeling of the K-band data. In Bruzual's scheme for luminosity evolution (with the rate of star formation depending on the available gas), these redder components become more important at higher redshifts because of their enhanced luminosities. Our no-evolution calculation uses the spectral energy distributions as they are at an age of 16 Gyr, and the bluer classes are generally of greater significance because of their smaller K-corrections. In the following we explore just the results of this no-evolution case, which provide a working null hypothesis with the fewest extra parameters.

The spectral energy distributions predict $V-K$ colors for elliptical galaxies that are too blue by 0.3 mag compared to direct measurements. A potentially more serious problem is the funneling of all models to a common very blue observed color, $b_J - r_F \sim 0$, at $z > 1$. The colors of galaxies at $z > 1$ may actually be spread over a redder range by internal extinction, which would explain the absence of an observed spike at $b_J - r_F \sim 0$ in the faintest intervals shown in Figure 2. The ability of the models to match the observed color-redshift relation (Figure 3) is however some testimony to the overall accuracy of the spectral energy distributions, at least for $z < 0.7$.

With respect to models of other investigators, ours is relatively complex regarding the specification of the input galaxy parameters, but we find this complexity to be necessary, since the broad range of observed colors at all magnitudes suggests that the counts are not dominated by any small number of categories of galaxies.

We have adopted $q_0 = 0$ because the enhanced volume element with respect to $q_0 = 0.5$ provides the needed higher faint counts. As found by Guiderdoni & Rocca-Volmerange (1990) and others, low q_0 and H_0, and correspondingly large ages for present-day galaxies, make the predicted evolutionary effects at a given redshift smaller, another desirable property.

In order to keep the results general, we have not modeled photometric errors nor the incompleteness of image detection, although as we stressed earlier, any detailed comparison to data should do so.

The specific model components—principally, the density and luminosity normalizations for the individual luminosity functions assigned to the respective spectral energy distributions—were determined interactively. [In principle, the procedure could be automated—see Bruzual (1990).] Of prime importance were the observed $b_J - r_F$ color distributions (Figure 2) and redshift distributions (Figure 5). We allowed the no-evolution model to under-predict the redshifts observed in faint samples (Figure 5) in anticipation that mild luminosity evolution would provide a better fit. The color distributions at bright magnitudes are fit by construction. The success of the model to fit the color distribution at faint magnitudes ensures that the spectral energy distributions, and their assigned distribution over luminosity, are at least adequate. The key unconstrained prediction involves the galaxy counts, shown in Figure 1.

Our no-evolution model for the blue counts curves gradually from the Euclidean expectation at bright magnitudes to flatter slopes at fainter magnitudes. When normalized to galaxy counts at $B = 18$, it falls short by a factor of 2 to 3 of the data some 8 magnitudes fainter (and most of this excess is already apparent by $b_J \sim 23$, i.e. within reach of spectroscopic investigation). A similar situation pertains to the red counts, whereas the no-evolution model fits the K-band counts very well. Considering all of the uncertainties in both the data and the model, we regard these simultaneous fits to be remarkably good. Any enhancement of star formation rates in the past will presumably serve to raise selectively the faint blue and red counts with respect to the K-band counts. Since even the no-evolution model predicts that at $B = 25.5$ the median redshift is appreciable ($z = 0.9$), any evolutionary effects are evidently mild so as not to predict too many high-redshift galaxies at brighter magnitudes.

As indicated earlier, the model spectral energy distributions, if taken at face value, produce a spike in color at $b_J - r_F \sim 0$ for $b_J > 25$. Even if this feature were smeared out by observational error, the predicted color distribution at faint limits is still far bluer than actually observed, and the problem is aggravated if the star formation rate is higher at earlier epochs.

Maddox et al (1990) suggested that there was evidence for evolution at low redshifts because their counts were steeper than a no-evolution model in the range $17 < B < 19$. Figure 1 shows that in this range of magnitudes the data are steeper than even our model, which contains very blue and very low-luminosity galaxies. In general one would be surprised to see strong evolutionary effects at low redshifts, because it implies that the bulk properties of galaxies have been changing rapidly near the present epoch. There is no a priori reason to consider model galaxies that pass through such a phase late in their lives, and in particular, no compelling reason to believe that galaxies should be properly phased such that they show a strong collective effect close to the present epoch.

Sharp features in the count distribution are difficult to model since a wide range of absolute magnitudes and galaxy types contribute at each apparent magnitude. An increase by a factor of 1.6 in a 2-magnitude interval, as proposed by Maddox et al (1990), would represent such a sharp feature, but neither the color distribution nor the redshift distribution are unusual at these magnitudes. The evolutionary effects proposed by Maddox et al (1990) would be expected in the counts of galaxies in the r-band. These counts also show a moderately steep slope in the range $16 < r < 19$, but the difference between the data and the no-evolution model appears to be smaller. Galaxy luminosity evolution of the kind conventionally assumed does make some difference even at these low redshifts ($z < 0.1$). We attribute the effect noted by Maddox et al (1990) to some combination of model uncertainties and conventional evolution. In principle there could also be systematic errors in the data or distortion due to very large-scale structure in the galaxy distribution, but such would have to be true also for the other galaxy-count studies that have covered the same range of magnitudes with similar results.

Our predicted no-evolution K-band counts are also shown in Figure 1. It is important to note that these predicted counts, like the predicted r-band counts, are plotted without any extra degree of freedom, since for each galaxy of magnitude B, the K magnitude follows from its apparent $B-K$ color. The $R-K$ and $B-K$ colors in our model approximately match the distributions of Elston et al (1990) and Cowie et al (1992), respectively, especially after the offset of 0.3 mag in $V-K$ mentioned earlier is taken into account. The predicted K-band counts initially rise more steeply than the blue counts because the K-corrections are smaller, and the counts then flatten to a shallower slope as the relatively local blue galaxies make up an increasing proportion of the faint counts in the b_J band. This expected behavior is just what the data show—the very faint K-band counts of Cowie et al (1992) are slightly lower, and have a shallower slope, with respect to the blue counts at an equivalent faint limit.

These features were interpreted by Cowie et al (1992) to indicate that $\Omega \sim 1$ on the assumption that the K-band counts are a more robust measure of volume than the B-band counts, because galaxy spectral energy distributions at long wavelengths are dominated by older stars. If $\Omega = 1$ is assumed, the apparent excess of blue galaxies with respect to the corresponding B-band count prediction is greater, which they attribute to a strongly evolving, lower luminosity, blue population that has since faded beyond recognition in local samples. According to our model, it is in fact not necessary to invoke ad hoc evolutionary processes to understand the K-band counts and the $B-K$ colors, nor to conclude that $\Omega = 1$.

4. CONCLUSIONS

Roughly a thousand spectroscopic redshifts have now been obtained for field galaxies at $z > 0.1$. The spectra reveal a distribution of redshifts at each magnitude that is not far from what is expected, at least for $B < 21$ ($z_{\rm med} \sim 0.2$) where evolutionary effects are supposedly small. Fainter than this, the predicted no-evolution median redshift falls short of that observed, which can be understood if galaxies experienced higher rates of star formation at moderate redshifts. The observed samples at $B > 20$ contain some low-luminosity galaxies, $L < 0.01\ L^*$, but the fraction of such low-luminosity galaxies appears to be at least qualitatively consistent with what is known from brighter samples. Moreover, high-luminosity galaxies appear in about the expected numbers. Thus, the redshifts so far obtained in surveys of faint galaxies are broadly consistent with models which predict modest evolutionary brightening for $z \lesssim 1$. More detailed conclusions cannot yet be made because it is clear that the inhomogeneous distribution of galaxies badly distorts the underlying redshift distribution, despite the combination of several fields. Large-scale structure is presumably also responsible for the significant differences between independently derived redshift distributions.

Bluer broadband colors are more sensitive to the formation of massive stars, and provide a direct way to test whether the star formation rate has changed with redshift. Nothing especially dramatic is evident in the color-redshift diagram (Figure 3), but the distribution of points is potentially sensitive to observational selection (galaxies at the highest measured redshifts will be those with strong spectral features at conveniently observed wavelengths). A less direct index of star formation is the strength of emission lines such as [O II] 3727. Since there is evidence that emission-line statistics may depend on galaxy luminosity, it is important to compare samples at different redshifts that comprise a similar range of absolute magnitudes. When this is done, the data do not show a change in the [O II] properties with redshift. (It has also not been demonstrated that local samples of galaxies with measured W_{3727} have been selected in a comparable way to the samples at $z > 0.1$.)

Photometric measurements extend several magnitudes fainter than the spectroscopic surveys, but the conclusions regarding evolution drawn from them are necessarily more model-dependent. The visible-band color distribution shows a smooth and relatively mild trend to bluer colors with increasing magnitude, without any clear signature of an additional population of galaxies with unusual redshifts or intrinsic colors. Before the small number of very blue (or, indeed, very red) faint galaxies can be properly interpreted, the error distribution in the measured colors and reliable statistics of galaxies with extreme colors in local samples need to be established. The distribution of galaxies in multicolor diagrams has been successfully modeled with conventional assumptions about the galaxy population and its evolution. The uncertainty in the spectral energy distributions in these models may explain the lack of detailed agreement, where such exists.

The counts in visible passbands show an excess at faint magnitudes with respect to a no-evolution model that assumes galaxies at high redshift are the same as they are locally. This effect has been known for a long time; newer counts extend the result to fainter magnitudes.

The *K*-band counts are better matched by the no-evolution model, although the significance of this may be lower because there are fewer surveys, each containing many fewer galaxies. The overall shape of the counts is well matched by a no-evolution model with $\Omega = 0$, and the normalization is consistent with the visible-band counts.

In this review, we have consolidated for the first time most of the existing data on B, R, and K galaxy counts; $B-R$ colors; and redshift distributions. The bulk of these measurements are based on relatively complete samples of faint field galaxies that range roughly from $B = 15$ to $B = 24$ for redshifts, and from $B = 15$ to $B = 28$ for imaging photometry. Virtually all of these data have been acquired over the past decade and represent an enormous advance in the depth and quality of information relating to the evolution of distant galaxies and to cosmology. To account for part of these data, different groups have proposed modifications to the conventional picture of mild luminosity evolution for $z \lesssim 1$. Examples include adoption of a large cosmological constant; substantial merging at low redshifts; a vast increase in bursting activity at moderate look-back times; or entirely new populations of galaxies that were present at high redshift but absent today. We have instead taken a more conservative stance and asked whether all the data might be found to be consistent with a simpler picture in which the cosmological constant is zero, the number of galaxies is conserved over time, and the shape of the luminosity function for each galaxy class is constant. Notwithstanding the new redshift data, we have argued that the combined uncertainties in the models and in the data so far preclude the necessity of more exotic assumptions.

We find that a no-evolution model for galaxies which incorporates a standard cosmology is able to account for most of the qualitative trends. One main exception is the possible need for mild luminosity evolution, consistent with existing redshift data, to explain the excess counts at faint visible-band magnitudes. The other evolutionary effects displayed by field galaxies are even more subtle and have not yet been detected with confidence. This area of research is likely to remain active (and controversial) for years to come.

ACKNOWLEDGMENTS

We thank colleagues who sent preprints and data. Howard Yee and Arati Chokshi were most helpful in creating the simulations shown in Figure 8, and Craig Mackay and Len Cowie provided the data used in the comparison. Puragra Guhathakurta provided the faint color data in Figure 2. A number of other collaborators have assisted in the acquisition of the unpublished data presented here, for which we acknowledge telescope time at KPNO and at CTIO. Richard Ellis and Tony Tyson made a number of valuable comments on an earlier draft. The model discussed here relies on the work of Gustavo Bruzual. John Smetanka, Nancy Ellman, and Greg Wirth provided important assistance, and Richard Dreiser prepared the figures and provided editorial help. This work has been supported by AST-8858203 (NSF PYI) and by AST-8705517.

Literature Cited

Arimoto, N., Yoshii, Y. 1986. *Astron. Astrophys.* 164: 260–73
Arp, H. 1966. *Ap. J. Suppl.* 14: 1–20
Baum, W. A. 1962. In *Problems of Extra-Galactic Research, IAU Symp.* 15, ed. G. C. McVittie, pp. 390–400. New York: MacMillan
Bergeron, J. 1991. *ESO Messenger No.* 62: 16–17
Bergeron, J., Boisse, P. 1991. *Astron. Astrophys.* 243: 344–66
Bershady, M., Hereld, M., Kron, R., Koo, D. 1990. In *Astrophysics with Infrared Arrays*, ed. R. Elston, pp.9–14. San Francisco: Astron. Soc. Pac.
Bohlin, R. C., Cornett, R. H., Hill, J. K., Hill, R. S., Landsman, W. B., et al. 1991. *Ap. J.* 368: 12–27
Broadhurst, T. J., Ellis, R. S., Glazebrook, K. 1992. *Nature* 355: 55–58
Broadhurst, T. J., Ellis, R. S., Shanks, T. 1988. *MNRAS* 235: 827–56
Brown, G. S., Tinsley, B. M. 1974. *Ap. J.* 194: 555–58
Bruzual, A. G. 1983. *Ap. J.* 273: 105–27
Bruzual, A. G. 1988. In *Towards Understanding Galaxies at Large Redshift*, ed. R. G. Kron, A. Renzini, pp. 161–176. Dordrecht: Kluwer
Bruzual, A. G. 1990. See Kron 1990, pp. 185–199
Butcher, H., Oemler, A. 1985. *Ap. J. Suppl.* 57: 665–91
Ciardullo, R. 1987. *Ap. J.* 321: 607–21
Chokshi, A., Wright, E. L. 1988. *Ap. J.* 333: 491–508
Code, A. D., Welch, G. A. 1982. *Ap. J.* 256: 1–12
Cole, S., Treyer, M. A., Silk, J. 1992. *Ap. J.* 385: 9–25
Coleman, G. D., Wu, C.-C., Weedman, D. W. 1980. *Ap. J. Suppl.* 43: 393–416
Colless, M., Ellis, R. S., Taylor, K., Hook, R. N. 1990. *MNRAS* 244: 408–23
Couch, W. J., Ellis, R. S., Godwin, J., Carter, D. 1983. *MNRAS* 205: 1287–312
Couch, W. J., Newell, E. B. 1984. *Ap. J. Suppl.* 56: 143–92
Cowie, L. L. 1988. In *The Epoch of Galaxy Formation*, ed. C. S. Frenk, R. S. Ellis, T. Shanks, A. F. Heavens, J. A. Peacock, pp. 31–38. Dordrecht: Kluwer
Cowie, L. L., Gardner, J. P., Hu, E. M., Wainscoat, R. J., Hodapp, K. W., 1992. Preprint
Cowie, L. L., Gardner, J. P., Lilly, S. J., McLean, I. 1990. *Ap. J. Lett.* 360: L1–L5
Cowie, L. L., Lilly, S. J. 1990. See Kron 1990, pp. 212–27
Cowie, L. L., Lilly, S. J., Gardner, J., McLean, I. S. 1988. *Ap. J. Lett.* 332: L29-L32
Cowie, L. L., Songaila, A., Hu, E. M. 1991. *Nature* 354: 460–61
Crampin, J., Hoyle, F. 1961. *MNRAS* 122: 27–33
Davis, M., Geller, M. J. 1976. *Ap. J.* 208: 13–19
Djorgovski, S., Spinrad, H., McCarthy, P., Strauss, M. A. 1985. *Ap. J. Lett.* 299: L1-L5
Dressler, A., Gunn, J. E. 1982. *Ap. J.* 263: 533–45
Dressler, A., Gunn, J. E. 1992. *Ap. J. Suppl.* 75: 1–60
Efstathiou, G., Bernstein, G., Katz, N.,

Tyson, J. A., Guhathakurta, P. 1991. *Ap. J. Lett.* 380: L47-L50
Ellis, R. 1987. In *Observational Cosmology, IAU Symp.* 124, ed. A. Hewitt, G. Burbidge, L. Z. Fang, pp. 367–81. Dordrecht: Reidel
Ellis, R. S., Allen, D. A. 1983. *MNRAS* 203: 685–93
Elston, R., Bechtold, J., Lowenthal, J., Rieke, M. 1991. *Ap. J. Lett.* 373: L39–L42
Elston, R., Rieke, G., Rieke, M. 1990. In *Astrophysics with Infrared Arrays*, ed. R. Elston, pp. 3–8. San Francisco: Astron. Soc. Pac.
Gibson, B. K., Hickson, P. 1991. In *The Space Distribution of Quasars*, ed. D. Crampton, pp. 80–83. San Francisco: Astron. Soc. Pac.
Giovanelli, R., Haynes, M. P., Chincarini, G. L. 1986. *Ap. J.* 300: 77–92
Giovanelli, R., Haynes, M. P. 1991. *Annu. Rev. Astron. Astrophys.* 29: 499–541
Gray, P. M. 1986. *Proc. SPIE* 627: 96-
Guhathakurta, P. 1991. PhD dissertation. Princeton Univ.
Guhathakurta, P., Tyson, J. A., Majewski, S. R. 1990a. *Ap. J. Lett.* 357: L9-L12
Guhathakurta, P., Tyson, J. A., Majewski, S. R. 1990b. See Kron 1990, pp. 304–6
Guiderdoni, B., Rocca-Volmerange, B. 1987. *Astron. Astrophys.* 186: 1–21
Guiderdoni, B., Rocca-Volmerange, B. 1990. *Astron. Astrophys.* 227: 362–78
Gunn, J. E. 1982. In *Astrophysical Cosmology*, ed. H. A. Bruck, G. V. Coyne, M. S. Longair, pp. 233–262. Vatican City State: Specola Vaticana
Hall, P., Mackay, C. D. 1984. *MNRAS* 210: 979–92
Hamilton, D. 1985. *Ap. J.* 297: 371–89
Heckman, T. M., Lehnert, M. D., Miley, G. K., van Breugel, W. 1991a. *Ap. J.* 282: 373–85
Heckman, T. M., Lehnert, M. D., van Breugel, W., Miley, G. K. 1991b. *Ap. J.* 370: 78–102
Heydon-Dumbleton, N. H., Collins, C. A., MacGillivray, H. T. 1989. *MNRAS* 238: 379–406
Hill, J. M., Angel, J. R. P., Scott, J. S., Lindley, D., Hintzen, P. 1980. *Proc. SPIE* 331: 279–88
Hintzen, P., Romanishin, W., Valdes, F. 1991. *Ap. J.* 366: 7–15
Hu, E. H., Songaila, A., Cowie, L. L., Stockton, A. 1991. *Ap. J.* 368: 28–39
Hubble, E., Tolman, R. C. 1935. *Ap. J.* 82: 302–37
Huchra, J. P. 1977. *Ap. J. Suppl.* 35: 171–95
Humason, M. L. 1936. *Ap. J.* 83: 10–22
Humason, M. L., Mayall, N. U., Sandage, A. R. 1956. *Astron. J.* 61: 97–162
Infante, L., Pritchet, C., Quintana, H. 1986. *Astron. J.* 91: 217–25
Jones, L. R., Fong, R., Shanks, T., Ellis, R. S., Peterson, B. A. 1991. *MNRAS* 249: 481–97
Jones, L. R., Shanks, T., Fong, R. 1988. In *Large Scale Structures of the Universe, IAU Symp.* 130, ed. J. Audouze, M.-C. Pelletan, A. Szalay, p. 528. Dordrecht: Kluwer
King, C. R., Ellis, R. S. 1985. *Ap. J.* 288: 456–64
Kirshner, R. P., Oemler, A., Schechter, P. L. 1978. *Astron. J.* 83: 1549–63
Kirshner, R. P., Oemler, A., Schechter, P. L., Shectman, S. A. 1983. *Astron. J.* 88: 1285–300
Koo, D. C. 1985. *Astron. J.* 90: 418–40
Koo, D. C. 1986. *Ap. J.* 311: 651–79
Koo, D. C. 1990. See Kron 1990, pp. 268–85
Koo, D. C., Kron, R. G. 1987. In *Observational Cosmology, IAU Symp.* 124, ed. A. Hewitt, G. Burbidge, L. Z. Fang, pp. 383–88. Dordrecht: Reidel
Koo, D. C., Szalay, A. S. 1984. *Ap. J.* 282: 390–97
Kron, R. G. 1980a. *Ap. J. Suppl.* 43: 305–25
Kron, R. G. 1980b. *Phys. Scr.* 21: 652–61
Kron, R. G. 1989. In *Astronomy, Cosmology, and Fundamental Physics*, ed. M Caffo, R. Fanti, G. Giacomelli, A. Renzini, pp. 383–98. Dordrecht: Kluwer
Kron, R. G., ed. 1990. *Evolution of the Universe of Galaxies—The Edwin Hubble Centennial Symposium.* San Francisco: Astron. Soc. Pac.
Lilly, S. J., Cowie, L. L., Gardner, J. P. 1991. *Ap. J.* 369: 79–105
Loh, E. D. 1988. In *Large Scale Structures of the Universe, IAU Symp.* 130, ed. J. Audouze, M.-C. Pelletan, A. Szalay, p. 529. Dordrecht: Kluwer
Loh, E. D., Spillar, E. J. 1986. *Ap. J.* 303: 154–61
Lowenthal, J. D., Hogan, C. J., Green, R. F., Caulet, A., Woodgate, B. E., et al. 1991. *Ap. J. Lett.* 377: L73-L77
Lowenthal, J. D., Hogan, C. J., Leach, R. W., Schmidt, G. D., Foltz, C. B. 1990. *Ap. J.* 357: 3–7
Maddox, S. J., Sutherland, W. J., Efstathiou, G., Loveday, J., Peterson, B. A. 1990. *MNRAS* 247: 1P–5P
Majewski, S. R. 1988. In *Towards Understanding Galaxies at Large Redshift*, ed. R. G. Kron, A. Renzini, pp. 203–7. Dordrecht: Kluwer
Majewski, S. R. 1989. In *The Epoch of Galaxy Formation*, ed. C. S. Frenk, R. S. Ellis, T. Shanks, A. F. Heavens, J. A. Peacock, pp. 85–88. Dordrecht: Kluwer

Matthews, T. A., Sandage, A. R. 1963. *Ap. J.* 138: 30–56
Mellier, Y., Fort, B., Soucail, G., Mathez, G., Cailloux, M. 1991. *Ap. J.* 380: 334–43
Metcalfe, N., Fong, R., Shanks, T., Kilkenny, D. 1989. *MNRAS* 236: 207–34
Metcalfe, N., Shanks, T., Fong, R., Jones, L. R. 1991. *MNRAS* 249: 498–522
Minkowski, R. 1961. *Ap. J.* 132: 908–10
Mobasher, B., Ellis, R. S., Sharples, R. M. 1986. *MNRAS* 223: 11–37
Neuschaefer, L. W., Windhorst, R. A., Dressler, A. 1991. *Ap. J.* 382: 32–43
Oke, J. B. 1983. In *Clusters and Groups of Galaxies*, ed. F. Mardirossian, G. Giuricin, M. Mezzetti, pp. 99–107. Dordrecht: Reidel
Peebles, P. J. E. 1980. *The Large Scale Structure of the Universe*. Princeton: Princeton Univ. Press
Pence, W. 1976. *Ap. J.* 203: 39–51
Peterson, B. A., Ellis, R. S., Efstathiou, G., Shanks, T., Bean, A. J., Fong, R., Zen-Long, Z. 1986. *MNRAS* 221: 233–55
Phillipps, S., Davies, J. I., Disney, M. J. 1990. *MNRAS* 242: 235–40
Picard, A. 1991. *Astron. J.* 102: 445–53
Pritchet, C. J., Hartwick, F. D. A. 1987. *Ap. J.* 320: 464–67
Pritchet, C. J., Hartwick, F. D. A. 1990. *Ap. J. Lett.* 355: L11-L13
Pritchet, C., Infante, L. 1986. *Astron. J.* 91: 1–5
Pritchet, C., Kline, M. I. 1981. *Astron. J.* 86: 1859–69
Rakos, K. D., Fiala, N., Schombert, J. M. 1988. *Ap. J.* 328: 463–74
Rocca-Volmerange, B., Guiderdoni, B. 1988. *Astron. Astrophys. Suppl. Ser.* 75: 93–106
Sandage, A. R. 1961. *Ap. J.* 134: 916–26
Sandage, A. 1988. *Annu. Rev. Astron. Astrophys.* 26: 561–630
Sandage, A., Tammann, G. A. 1981. *A Revised Shapley-Ames Catalog of Bright Galaxies*. Washington: Carnegie Inst. Washington
Schild, R., Oke, J. B. 1971. *Ap. J.* 169: 209–14
Sebok, W. L. 1986. *Ap. J. Suppl.* 62: 301–30
Shanks, T. 1990. In *Galactic and Extragalactic Background Radiation: Optical, Ultraviolet, and Infrared Components*, *IAU Symp.* 139, ed. S. Bowyer, Ch. Leinert, pp. 269–81. Dordrecht: Kluwer
Shanks, T., Stevenson, P. R. F., Fong, R., MacGillivray, H. T. 1984. *MNRAS* 206: 767–800
Smith, H. E., Cohen, R. D., Burns, J. E., Moore, D. J., Uchida, B. A. 1989. *Ap. J.* 347: 87–95
Songaila, A., Cowie, L. L., Lilly, S. J. 1990. *Ap. J.* 348: 371–77
Steidel, C. C., Sargent, W. L. W., Dickinson, M. 1991. *Astron. J.* 101: 1187–95
Stevenson, P. R. F., Shanks, T., Fong, R., MacGillivray, H. T. 1985. *MNRAS* 213: 953–69
Stevenson, P. R. F., Shanks, T., Fong, R. 1986. In *Spectral Evolution of Galaxies*, ed. C. Chiosi, A. Renzini, pp. 439–46. Dordrecht: Reidel
Thompson, D. J., Djorgovski, S. 1991. *Ap. J. Lett.* 371: L55-L57
Tinsley, B. M. 1972. *Ap. J.* 178: 319–36
Tinsley, B. M. 1980. *Ap. J.* 241: 41–53
Turner, E. 1980. In *Objects of High Redshift*, *IAU Symp.* 92, ed. G. O. Abell, P. J. E. Peebles, pp. 71–72. Dordrecht: Reidel
Turnshek, D. A., Macchetto, F., Bencke, M. V., Hazard, C., Sparks, W. B., McMahon, R. G. 1991. *Ap. J.* 382: 26–31
Tyson, J. A. 1984. In *Astronomy with Schmidt-Type Telescopes*, ed. M. Capaccioli, pp. 489–98. Dordrecht: Reidel
Tyson, J. A. 1986. *Astron. J.* 92: 691–99
Tyson, J. A. 1988. *Astron. J.* 96: 1–23
Tyson, J. A. 1990. In *After the First Three Minutes*, *AIP Conference Proceedings* 222, ed. S. S. Holt, C. L. Bennett, V. Trimble, pp. 437–45. New York: Am. Inst. Phys.
Tyson, J. A., Seitzer, P. 1988. *Ap. J.* 335: 552–83
Tyson, J. A., Valdes, F., Wenk, R. A. 1990. *Ap. J. Lett.* 349: L1-L4
Wang, B. 1991. *Ap. J. Lett.* 383: L37–40
Wells, D. C. 1972. PhD dissertation. Univ. Texas
Wolfe, A. M., Turnshek, D. A., Lanzetta, K. M., Oke, J. B. 1992. *Ap. J.* 385: 151–72
Yanny, B. 1990. *Ap. J.* 351: 396–405
Yanny, B., York, D. G., Williams, T. B. 1990. *Ap. J.* 351: 377–95
Yee, H. K. C. 1991. *Publ. Astron. Soc. Pac.* 103: 396–411
Yee, H. K. C., Green, R. F., Stockman, H. S. 1986. *Ap. J. Suppl.* 62: 681–702
Yee, H. K. C., Green, R. F. 1987. *Ap. J.* 319: 28–43
Yoshii, Y., Fukugita, M. 1991. In *NATO Workshop on Observational Tests of Cosmological Inflation*, ed. T. Shanks et al., pp. 267–71
Yoshii, Y., Peterson, B. A. 1991. *Ap. J.* 372: 8–20

Annu. Rev. Astron. Astrophys. 1992. 30: 653–703

OBSERVATIONS OF THE ISOTROPY OF THE COSMI MICROWAVE BACKGROU RADIATION

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KEY WORDS: cosmology, galaxy formation, anisotropy

1. INTRODUCTION

Over the past decade the anisotropy of the microwave b ation has emerged as a field of fundamental importanc due to its significance in theories of galaxy formation an the physical origin of fluctuations. The history of the dev subject may be divided into three phases. In the first phas about 1982, searches for anisotropy were carried out o ranging from two arc minutes to 180°, and, apart from due to the peculiar velocity of the Earth relative to the F Fixsen et al 1983, Lubin et al 1985, Halpern et al 1985, lachev 1988, Meyer et al 1991b, Smoot et al 1991b), no a detected down to the level of $\Delta T/T \approx 10^{-4}$–$10^{-3}$ expec scenarios for galaxy formation. In the second phase, $\sim$1989, sensitivities were improved by a full order of still no intrinsic anisotropies were detected. Over the sa theoretical models were eliminated and new models wer predicted fractional anisotropies approaching 10^{-6}. We the third phase: Sensitivities on all angular scales have rea confusing signals due to discrete sources or diffuse Gal due to dust, free-free emission and synchrotron radiatio

0066–4146/92/0915–0653$02.00