THE DISTRIBUTION OF FAINT GALAXIES

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ABSTRACT: Faint galaxy data are reviewed in the context of standard evolutionary models and our understanding of the statistical properties of galaxy populations. The differences in number magnitude counts from group to group can largely be understood via fluctuations induced by large scale clustering. However count slopes still present convincing arguments for an extra component of faint blue galaxies beyond B $\sim$ 21. Colours provide an useful tool in estimating redshift distributions but the uncertainties are large for the bluest galaxies of interest. However, new faint object redshift surveys are now underway and promise to determine definitively the nature of this extra component. We discuss preliminary results from one of these surveys. Neither distant luminous galaxies nor intrinsically faint nearby galaxies appear to be very numerous to B = 21.5. Many of the galaxies with $0.2 < z < 0.4$ show spectral signatures of prominent star-formation. If such objects are somehow related to the excess counts, the traditional redshift-dependent evolutionary theory may require revision.

1. Introduction

A long-held view in observational cosmology is that the spectral evolution of galaxies and growth of large scale structure may be quantified from detailed studies of complete samples of faint galaxies. One disadvantage of this "all-object" approach is that the statistical properties of the various components of the galaxy population need to be well-understood before any evolution can be inferred. However, only with extensive and objectively-controlled surveys might one recognise selection effects otherwise hidden in probes of galaxy evolution based on studies of individual objects.

Historically the subject of faint galaxy studies is one of a gradual increase in detail. We begin with Olber's assessment of the finite integrated background and its implications for the effects of redshift and the evolutionary timescale, later come Hubble's counts of faint galaxies and his attempts to determine the curvature radius,

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these led to the modern realisation of the vast information content of multi-passband Schmidt and 4 metre telescope photographic plates for the subject of galaxy evolution. Previous reviews (Ellis 1982, Kron 1982, Koo 1984) have been limited to analyses of these photographic data and generally concluded that there is some evidence from the number and colour distributions of faint (B > 21) galaxies for mild evolution over recent look-back times.

The evolution claimed is only statistical; it is not straightforward, for example, to identify any distant evolving component from photometric data alone. Koo (1985) and Loh and Spillar (1986) have investigated the use of multicolour data to determine approximate redshifts with interesting results. Their approach is to some extent being overtaken by a new development. Progress in multiple object instrumentation such as fibre optic couplers (Ellis et al 1984) and multislit aperture plates (Koo 1983) at last makes it practical to collect genuine spectra to sufficiently faint limits. Redshift distributions allow us direct cosmological and evolutionary tests hitherto not possible. Spectral details can also be examined independent of any search for luminosity or colour changes. Finally, we can look forward to another increase of detail in our knowledge of faint galaxies via ultraviolet and morphological data from the Hubble Space Telescope.

This review is the first to discuss the new faint object redshift surveys. At least two such surveys are in progress and here I briefly review preliminary results from one of them. There are implications for our understanding of how galaxies evolve with redshift and the distribution of broad populations of galaxies seen in large volumes of space.

2. Statistical Properties of Normal Galaxies

A number of local redshift surveys have been performed in recent years but few have a well-defined photometric scale and cover large enough volumes to be representative. The B $\sim$ 16 - 17 magnitude-limited pencil beam surveys of Kirschner and colleagues (Kirschner et al 1978,1979,1981) and the Durham/AAT group (Peterson et al 1986) have shown that galaxies are not a single parameter (luminosity) family. Analytical representations are usually fitted to local luminosity functions (LFs) classed by morphology (Ellis 1982) or colour (Koo 1981). A subset of the Durham/AAT redshift survey (hereafter DARS) has recently been extended to infrared passbands (Mobasher et al 1986). The combination of morphologies and restframe B - K colours provides a valuable check on different ways to estimate the population mix and LFs. B - K offers a wide baseline with which to discriminate stellar populations and a reasonable correlation with morphology has already been shown (Aaronson 1978).

Table 1 shows numbers and Schechter (1976) LFs classed by morphology and colour to B = 16.85 from the DARS. We adopt a fixed faint end slope of α = -1.25 found by maximum likelihood fitting to the total sample (Bean 1983). The "B" photometric system here is the Kodak IIIa-J/Schott GG395 (= b_j)system at the 26.5 mags arcsec^{-2} isophote used in most faint studies (c.f. Peterson et al 1979, Shanks et al 1984). Table 1 shows a significant fading of the characteristic luminosity M_B for both later types and bluer colours. When spectral energy distributions are assigned to each type/colour class (from Pence (1976) in the optical and King and Ellis (1985) in the near ultraviolet), the no-evolution count-magnitude-redshift N(m,z) predictions for 20 < B < 23 are virtually identical whether one classifies by colour or morphology (c.f. Table 2).

Table 1

Type and Colour-dependent Luminosity Functions (H_o = 50)

Colour	No	M_B	Type	No	M_B
B - K > 3.65	74	-21.39	E/S0	97	-21.67
3.65 > B - K > 2.9	61	-21.24	Sa-Sbc	117	-21.20
2.9 > B - K	32	-20.52	Sc-Im	46	-21.31:
			Unclassed	39	-20.87:
			All(classed)	260	-21.28
All	167	-21.24	All	299	-21.48

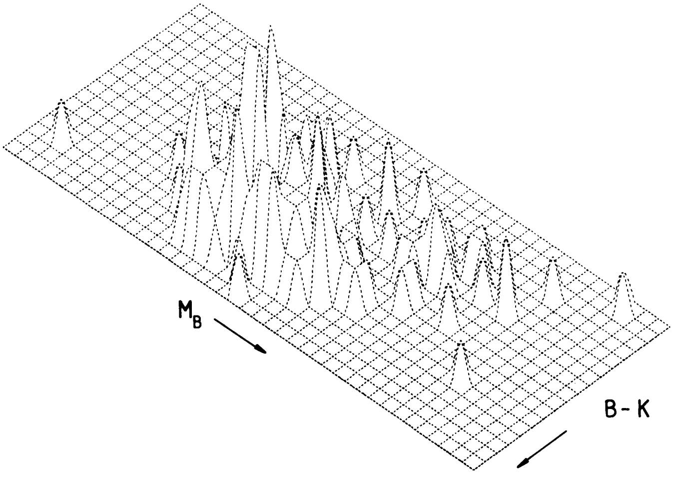

Fig. 1. Joint distribution of absolute B magnitude and restframe B-K colour for 170 DARS galaxies to B=17; note the tail of faint blue galaxies (H_o=50).

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Although much is known about the LF of dwarf (M_B > -18.5) galaxies in *clusters*, little is known about their overall space density. Fig. 1 shows these systems in the DARS are mostly blue Scd-Im galaxies which do not fit a standard Schechter function very well. They cannot be accounted for in faint predictions in a straightforward way yet their fraction of the total population *increases* at fainter apparent magnitudes since they suffer almost no redshift dimming. To B $\sim$ 17 there are 17 (5%) DARS galaxies with M_B > -18.5 in excess of the Schechter LFs. With the exception of a few dEs all show strong Oxygen emission lines with excitation typical of star forming regions. As Kron (1982) pointed out, it is premature to attribute the observed excess of 20-40% of faint galaxies at B $\sim$ 21 - 22 to luminosity evolution over the last few Gyr. A 5% excess of intrinsically faint blue galaxies at B $\sim$ 17, if representative by volume, would contribute 30% at B = 21.5. Only deeper redshift surveys can clarify this possibility.

3. Counts and Colours

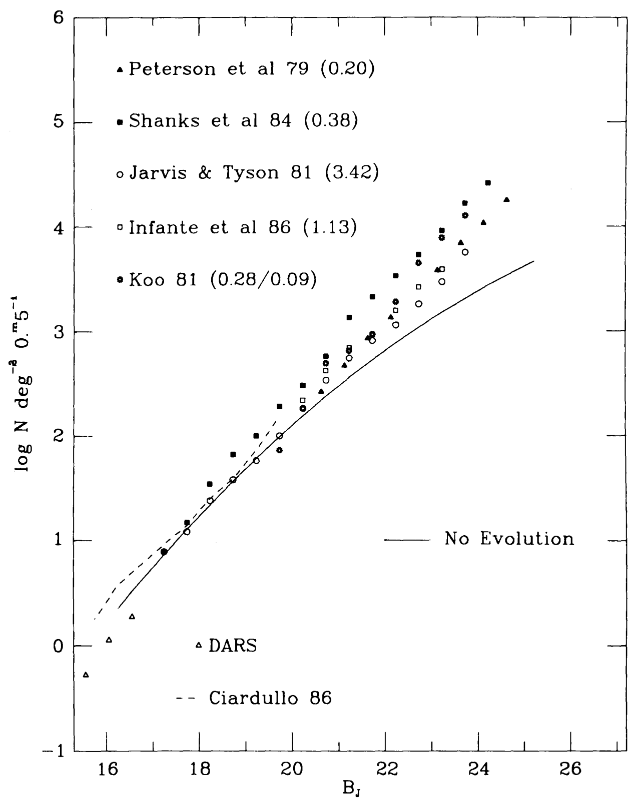

Fig. 2. Differential number magnitude counts in the photometric system defined in §2. The area (deg^2) appropriate to each published analysis is given. The model (solid line) assumes no evolution and properties of Table 1 with an absolute normalisation determined from Schmidt counts.

Standard evolutionary models (Tinsley 1978,1980, Bruzual 1983) predict a much greater sensitivity, at a fixed lookback-time, to changes in luminosity rather than colour (e.g. $0^m.4$ in observed B for each $0^m.1$ in B-V for models reproducing present day ellipticals with ages 16 Gyr). Since numbers increase steeply with distance, counts are still the most sensitive and objective probe. The models assume that galaxies of an individual type or colour class share a unique redshift-dependent evolutionary track irrespective of mass. Redshifts and colours for faint galaxies will allow us to examine this assumption.

The comparison of published counts (Fig. 2) shows substantial variations in the absolute number densities from group to group; it might be asked is the photometry reliable? The situation has now clarified considerably due to an increase in the number of 4m plates scanned and an international collaborative venture (Ellis and Koo 1986) to examine various software packages used for detection and photometry of faint galaxies. Standard intensity-calibrated photographic data was sent to each group who used their own algorithms for detection, photometry and image classification. Koo and I collated and compared the various catalogues. A preliminary analysis shows that for detection the groups agree remarkably well to about B = 23.5 - 24.0, close to our estimate of the completeness limit of the data. However, the galaxy photometry becomes seriously discrepant amongst some groups beyond B $\sim$ 23 (Fig. 3). Only part of this effect is the expected difference between isophotal and "total" magnitudes (Ellis 1982, Kron 1982, Shanks et al 1984); in those cases where the group catalogues listed the local sky estimate, it was apparent that its determination is a major uncertainty also. Deeper CCD data has now been procured to determine improved independent parameters for the objects. Meanwhile we conclude that the scatter in the galaxy counts arising from different measurement schemes should be small provided comparisons are made brighter than B $\sim$ 23.

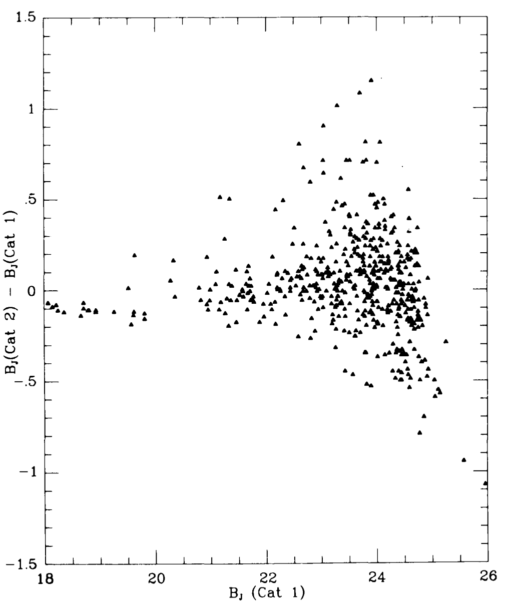

Fig. 3. A comparison of two different photometric reductions applied to a standard photographic data set supplied to a number of groups by Ellis and Koo (1986).

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In collaboration with colleagues at Durham, the photographic counts have been extended to 5 more 4 metre fields; each has good CCD calibrations to better than $\pm 0^m.20$. In the range $20 < B < 22.5$ the fluctuations between 1 $\deg^2$ areas are about 5 times those expected from Poisson noise with a peak-to-peak range of $\sim \times 1.6$, i.e. consistent with Fig. 2 using one reduction technique. Furthermore, comparisons of Schmidt plate counts with IRAS and H I data (Fong et al 1986) appear to rule out Galactic extinction as a source for the fluctuations and we conclude large scale clustering is most likely responsible (see $4). These fluctuations have serious repercussions for deeper magnitude count programmes using CCDs.

Fig. 2 also includes the no-evolution prediction derived from the LFs discussed in $2; the dependence on q_o is minimal. For reasons that are not well-understood, the absolute normalisation of the DARS is $\sim \times 2$ lower than that obtained from deeper Schmidt counts (Shanks et al 1984, Ciardullo 1986). Because of this and the fluctuations discussed above we will quantify the deviation of the observations from the model via the slope of the counts in the range $21 < B < 23$ (Table 2).

Table 2

Galaxy Count Slopes $21 < B < 23$

Observations:		No evolution models:	
Peterson et al 1979	0.46	King and Ellis (1985)	0.365
Koo 1981	0.47	Koo and Szalay (1985)	0.36
Jarvis and Tyson 1981	0.40	This work:	
Shanks et al 1984	0.48	morphological LFs	0.340
Infante and Pritchet 1986	0.40	B - K LFs	0.339

Adopting the Schmidt count normalisation, the excess at $B = 21.5$ is about 30% rising to a factor of 2 by $B = 22.5$. The most puzzling aspect of the observed slope is its constancy over a very wide range of apparent magnitude; unpublished CCD data analysed by Tyson (private communication) suggests the slope extends to $B = 26$ *with no features*. Although any slope steeper than 0.40 continued indefinitely would produce a divergent extragalactic background light (EBL), even to $B = 28$ the contribution is still an order of magnitude less than the most stringent lower limit on the direct measurement of the EBL (Dube et al 1979).

Koo (1981, 1986) has shown the slope of the counts depends on wavelength in a fairly systematic way - decreasing from a Euclidean 0.6 in the U to a sub-Euclidean 0.4 in F and N, i.e the extra objects are blue - a point originally made by Kron (1980) on the basis of two passbands. The colour of a galaxy depends on its restframe spectral energy distribution (SED) and redshift. It might thus be possible to infer approximate redshift distributions of faint galaxies from multicolour data alone. However if any spectral evolution is present, this will distort the form of the SED and the inferred N(z). Precise modelling may salvage the situation but the approach is rather restrictive when the evolutionary behaviour of galaxies is largely unknown.

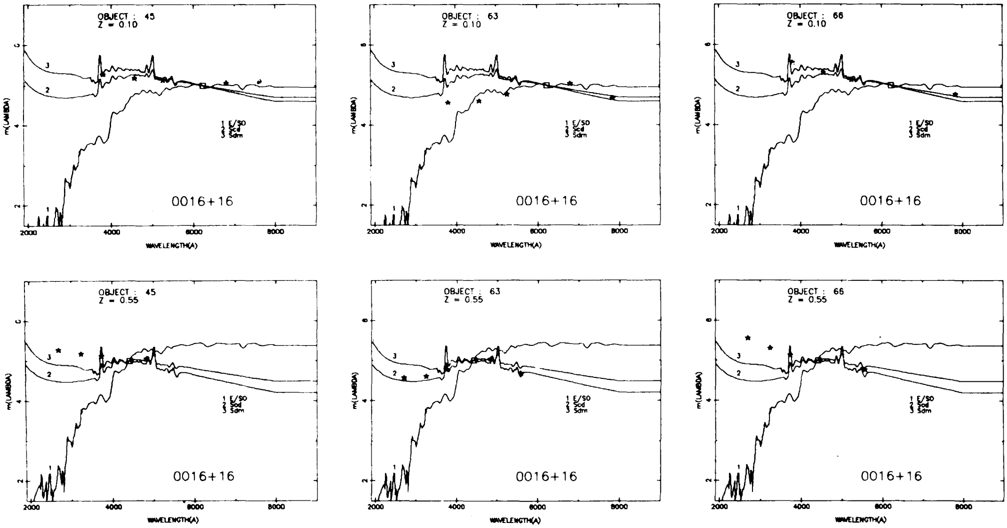

Fig. 4. Uncertainties in estimating redshifts from multi-colour data: 6 colour CCD data (*) for blue galaxies in the cluster 0016+16 (Ellis et al. 1985) compared with local SEDs (lines) assuming z=0.10 and z=0.55. Object 63 has a spectroscopic redshift of 0.54.

First we review the application of multicolour redshift estimation in distant clusters where there is often detailed CCD photometry of high precision *and* spectroscopic redshifts. Couch et al (1983) have developed a CCD imaging system based on 6 intermediate-band filters for monitoring evolution in early type galaxies. Simulations using present day SEDs suggest a greater sensitivity to fainter limits than that based on broad-band photographic UJFN. For early type galaxies the method is extremely successful and spectroscopically supported (MacLaren 1987). However, even with 5% precision over 4000-9000 A, the redshifts of later type galaxies are very difficult to determine to better than ± 0.2 in z (Fig. 4; c.f. Koo (1986) Fig 9). In addition to difficulties associated with featureless SEDs, there is evidence that "abnormal" systems unrecognised at present epochs will confuse matching algorithms (Ellis et al 1985). Colours alone may therefore be unable to identify and provide redshifts for hitherto unknown classes of objects. On the other hand the combination of colours *and* spectra within a given magnitude range may be a very powerful way of extending an otherwise restricted data set to include many hundreds of faint galaxies (c.f Loh and Spillar 1986).

Koo (1986) claims from his photographic UJFN estimated redshifts and over a hundred spectroscopically determined, that his method is accurate to ± 0.05 in z. (A similar claim is made by Couch et al for their 6 colour CCD-based system but upheld only for the E/S0s and early/mid-range spirals). Koo estimates the fraction of field galaxies with rest-frame colours bluer than B - V = 0.7 has doubled at $z \sim 0.4$ and that, presumably, this contributes to the excess of field counts since the uv and blue luminosity functions will be shifted brightward. However, the redshift estimates for these bluest galaxies will be the most uncertain and again only spectroscopic surveys can rule out the alternative hypothesis that these extra blue galaxies are, in fact, intrinsically faint galaxies at lower redshifts.

4. Faint Redshift Surveys

8 years after the original magnitude count papers of Kron(1978), Peterson et al (1979) and Tyson and Jarvis (1979) it is now possible to obtain redshifts at interesting limits. Faster spectrographs and detectors are partly responsible but the major factor is multiple object work that encourages the observational astronomer to make the necessary long exposures. At the IAU Symposium 104 in Crete, the subject was just beginning with surveys reported by Koo (1983) and Ellis (1983). These surveys deeper than B = 20 now have over 200 redshifts each (Table 3) and I will discuss preliminary results derived from the AAT survey done in collaboration with Broadhurst and Shanks.

Table 3

Deep Redshift Surveys

	Koo, Kron and Szalay	Ellis, Broadhurst and Shanks
Telescope:	KPNO 4.0m	AAT 3.9m
Instrument:	CryoCam + TI CCD	RGO + IPCS / FORS + GEC CCD
Multiplex gain:	20 holes/8 slits	50 + 50 fibres
Range (A)	4500 - 7500	3700 - 6100 / 5000 - 10,000
Resolution (A)	15	4 / 15
Exposures (hr)	1 - 4	4 - 6
Magnitude limit	R < 20	20 < B < 21.5

The only other complete survey known to the author is that of Tritton and Morton (1984) who catalogued $\sim$ 750 objects in a single field of 0.31 deg^2 area to B = 19.5 - 20 using low dispersion objective prism spectroscopy. Since *all* objects were scrutinised spectroscopically the ratio of stars/galaxies checks how many extragalactic objects are masquerading as stars e.g. because of their compact nature. The number of galaxies found by spectroscopic means was about 140 in close agreement with that expected from image classifications. To date only 45 of these have reliable redshifts from grating spectroscopy though further work is planned (Morton, private communication).

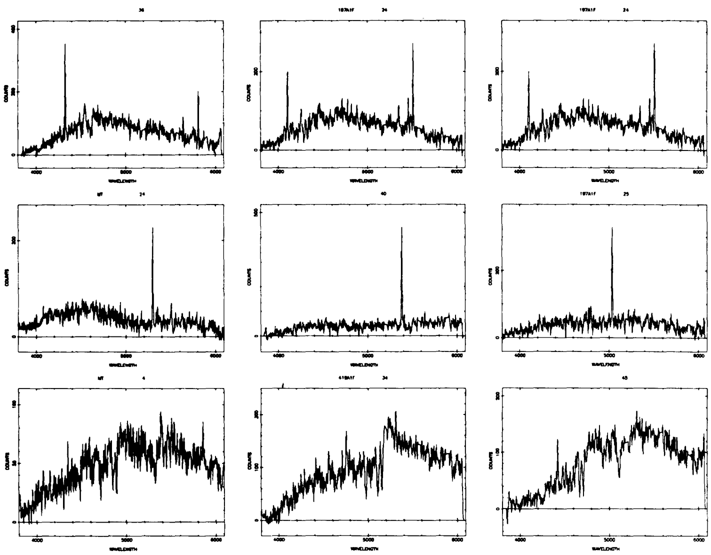

Fig. 5. Sample spectra for galaxies with $\langle B \rangle \sim 21-21.5$ from the AAT faint survey; (top) $0<z<0.22$ showing [O II] and [OIII], (centre) $0.22 <z<0.45$ showing [O II] alone and (bottom) absorption line objects with various redshifts.

The AAT faint survey is complementary to that being pursued at KPNO because the galaxies are selected in B purposely to investigate the count excess. The multiplex advantage with fibres is larger with fewer geometrical restrictions on the target distribution. Longer exposures can thus be afforded and the high success rate on a first exposure ($\sim$ 75% in $\sim$ 4 hours) is obtained with intermediate (rather than low) dispersion. Slits are doubtless better for the faintest targets with B > 22 (we have recently commissioned a wide field multislit spectrograph on the AAT (Ellis and Taylor 1986) with which deeper surveys can continue) but fibres offer many advantages in the window 20 < B < 21.

The AAT survey is currently 85% complete to B = 21 and 75% complete to B = 21.5, with $\sim$200 redshifts secured. Since the AAT galaxies are confined to a narrow magnitude slice, the z distribution is the most informative probe of any evolution particularly at the low ($z < 0.1$) and high ($z > 0.4$) ends. Completeness is thus an important issue. Fortunately we can check the observed redshift distribution is representative in a number of ways. A large proportion of spectra (50%) to B = 21.5 show both [O II] 3727 and [O III] 5007 yielding unambiguous redshifts for $0 < z < 0.22$ (Fig. 5). A smaller proportion (35%) show a single emission feature taken to be [O II] with $0.22 < z < 0.6$ since we can often readily identify the Balmer absorption lines, also no single feature is ever seen in the low z range where 5007 could also be detected.

We observe a marked decline in N(z) for $z > 0.3$ well within the range discussed above, i.e. there is no detectable high z tail corresponding to luminous evolving galaxies. The Faint Object Red Spectrograph (FORS) covers the window 0.5 - 1 microns at sufficient dispersion for [O II] to be visible if present thus we would probably detect any galaxies with emission lines with $z < 1$. For absorption lines, only the low redshift range $z < 0.5$ is well covered, the principal features being Ca II and the Balmer sequence; the FORS resolution is mostly inadequate. Failures turn out to be mostly objects whose continuum signal is too faint for redshift work - a few are extended low surface brightness objects. Very few objects are featureless at this dispersion.

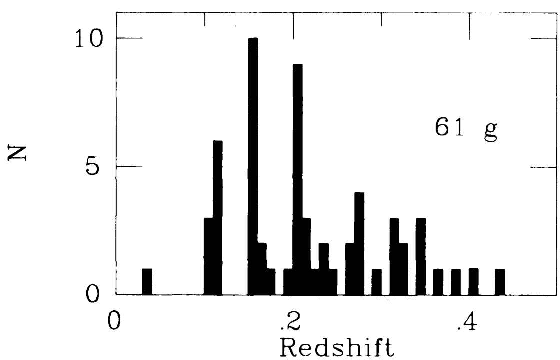

Fig. 6. Preliminary redshift distribution for one of 5 fields in the AAT faint galaxy survey.

The complete catalogue and analysis will be presented elsewhere but a preliminary N(z) for one of the 5 fields is reproduced in Fig. 6. Analysis of the distribution for all fields indicates a reasonable agreement between the data and the no evolution prediction. The mean redshift for 200 galaxies with $20 < B < 21.5$ is $\langle z \rangle = 0.222 \pm 0.010$, compared with 0.231 for no evolution . Were the early type galaxies to evolve in luminosity along the lines of Bruzual's $\mu = 0.5$ model, $\langle z \rangle$ would rise to 0.25. Actually this would not be sufficient to explain the steep count slope to B = 23; stronger evolution is required pushing $\langle z \rangle$ above 0.30. Although more complete data is desirable, the absence of any such high z tail in the observed distribution suggests there is not yet any evidence for luminosity evolution over the last 5 Gyr.

The faint count excess cannot reasonably be due to large numbers of low luminosity galaxies either. We can match the steep count slope by incorporating a sizeable population of $M_B > -18.5$ galaxies. 12% to B = 16.85 are needed to raise the no evolution slope to 0.41 (c.f. 5% observed in DARS - §2). This would produce a low z hump in N(z) reducing <z> to 0.18. No such hump is observed. Incompleteness can be tested further by restricting the analysis to our 4 best fields with 20 < B < 21 where we have 85 galaxies representing a 90% complete sample. Again the no evolution model is a good fit to the observed distribution.

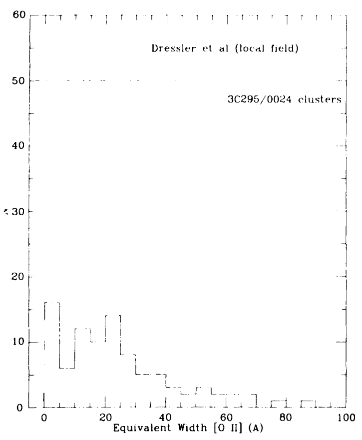

Fig. 7. Distribution of restframe equivalent widths for [O II] for the AAT faint galaxy survey (solid) and the nearb y DARS (dashed) with ranges shown for nearby field and distant cluster samples observed by Dressler et al.

One possible clue as to the nature of any excess comes from the surprising proportion of spectra showing strong [O II] emission, many have restframe equivalent widths > 20 A. The luminosities of these galaxies are not unusual but they seem to be undergoing proportionally much larger bursts of star formation than their counterparts in the nearby DARS surveys (Fig. 7). Interestingly, only the low luminosity objects nearby show such large [O II] widths, whereas at <z> ∿ 0.25 the effect is widespread amongst luminous galaxies.

There are two selection effects that might make distant galaxies show stronger emission lines - the aperture effect and the K-correction. The AAT fibre aperture at <z> = 0.2 is 13 kpc diameter whereas that in the DARS used for the comparison in Fig. 7 at <z> = 0.05 is a rectangle of 5 x 20 kpc. Dressler et al (1982,1985) have also observed a small sample of nearby spirals through a large aperture and find a range of [O II] widths similar to that in the DARS. Thus the aperture effect does not seem to be responsible. The K-correction effect whereby blue-selected galaxies at high z are more likely to be uv strong can be checked also since the relation between restframe colour and [O II] strength has been calibrated by Dressler et al. Colours are available for some of the faint AAT sample and too few uv galaxies are present to account for the emission line distribution.

To summarise, therefore, the redshift survey discussed has so far failed to find any obvious component responsible for the excess galaxy counts. There seems to be little evidence for any *systematic* evolution in any significant subset of the population over the last 5 Gyr. It may be that the count excess is an artefact of an incorrect no evolution slope and that, to B = 21.5, none would be expected. This seems unlikely given our reasonable knowledge of the field population, its mix and LF. The absolute normalisation of the galaxy counts does, however, play a vital role in assessing the excess (Fig. 2) and more well-calibrated counts in the 17 < B < 20 region are needed to check the effects of fluctuations.

On the other hand, it is interesting to speculate whether the strong emission line objects are related to the excess counts. Statistically complete large aperture spectroscopy of nearby galaxies is urgently needed to verify the trends suggested in Fig. 7. However, we note that a burst of star formation could, for a few Gyr, raise the luminosity of a low mass spiral (such as those in Fig. 1) to that required for appearance in the faint survey. Because only a subset of the LF might be prone to such bursts at any epoch (such as implied by the biased theory of galaxy formation), we would need to study the change in *shape* of the LF with epoch rather than to follow a systematic brightening of *all* galaxies with lookback-time.

5. Large Scale Structure and Galaxy Correlations

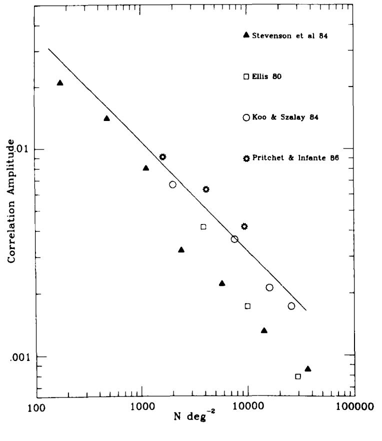

Fig. 8. Angular correlation amplitudes at 1 degree separation versus galaxy surface density for deep samples surveyed in B. The model shows the expected behaviour for stable clustering and no evolution.

Various groups nave analysed the angular correlations at faint magnitudes (Ellis 1980, Koo and Szalay 1984, Stevenson et al 1985, Pritchet and Infante 1986). Their results are inconsistent (Fig. 8).

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Ellis and Stevenson et al fitted a -0.8 power law to their two point function $w(\theta)$ but found an amplitude lower than expected for either virialised or comoving structures to B = 24. At B = 24 a significant fraction of galaxies would have $0.5 < z < 1$ and they concluded there was some evidence for growth in clustering over the last 10 Gyr.

Koo and Szalay found a flatter slope of -0.5 in their faintest samples but found room for some luminosity evolution. It is not possible to distinguish between the two forms of evolution via $w(\theta)$ alone, one needs the counts as well. Since the redshift distributions so far observed cast some doubts on the traditional N(m) interpretation, it is interesting to reconsider these conclusions based on the correlation analyses.

Interpreting correlation amplitudes for faint data is complex beyond the need for an adequate description of evolution in the LFs. For example, Davis and Geller (1978) showed ellipticals are more strongly clustered than spirals. In the DARS sample the -1.8 power law amplitude ratio for the spatial correlation function is about x 1.8. K-corrections increase the proportion of spirals in faint samples (from 60% at B = 16.85 to 80% at B = 24 for no evolution) and this affects the expected amplitudes at the 20% level. Contamination of data from spurious uncorrelated images (noise, stars) lower the amplitude according to the square of the contamination factor. Considering the software algorithm tests discussed earlier, these might cast doubt on the deepest points in Fig. 8 but not those at < 10^4 galaxies/deg^2 densities where discrepancies are still present.

Any correlation evolution might be more apparent in 3-D via the new redshift surveys since the major problem with the angular function is the projection effects which reduce the amplitude observed to $\sim$ 5% on scales of 1 arcmin to B $\sim$ 23. The spatial correlation function in the faint AAT survey does show an amplitude tantalisingly lower than expected in the virialised case but about twice the number of galaxies is needed before any significance can be attached to this result. It will be particularly interesting to examine whether the star-forming galaxies discussed in $4 are distributed any differently from the remainder.

Finally a comment on the large scale distribution of galaxies as exemplified in Fig. 6. In common with other talks at this symposium we can identify large sheet-like structures in the 3-D distribution for some but not all of our narrow angle ($\sim$20 arcmin) fields. Our sample covers perhaps the largest volume so far surveyed and thus might be expected to be the most representative of the universe on large scales - the average depth is 1000 Mpc (H_o = 50). The sheets explain in a natural way the fluctuations in the galaxy counts that puzzled the observers for so many years. There is a good correlation between the number of sheets "skewered" by each survey cone and the absolute number of galaxies counted to deeper limits in that area.

Hubble's goal of using the faint counts to confirm fairly preciselythe homogeneity of the Universe on large scales seems that bit further away.

6. Acknowledgements

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DISCUSSION

BAHCALL: Are the star-burst galaxies in the field fainter than those found in the z ~ 0.3-0.4 Butcher-Oemler clusters?

ELLIS: Not significantly in luminosity. A similar limiting magnitude was reached by Dressler et al. for clusters at redshifts slightly deeper than our average field redshift.

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