Faint galaxy surveys

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ABSTRACT Various K band galaxy surveys have now established 2.2-µm galaxy counts from K = 10 to K = 23. The K band counts rise slightly faster than a Euclidean slope to K = 17, at which point they turn over; beyond this magnitude, galaxies also become much bluer. Spectroscopic samples are available between K = 10 and 20 and show that the conventional distance laws hold rather precisely out to a redshift of about 0.6. Beyond this, galaxies appear fainter than expected. The results appear to favor rapid merging at modest galactic redshifts.

In principle, number counts of faint galaxies should be a powerful probe of the cosmological geometry, but in practice optical and radio galaxy counts contain much more information about the evolution of the galaxy or its nucleus than about the cosmology. The simple reason for this is that the nuclear activity responsible for the radio emission and the massive stars responsible for the blue light are transient events by cosmological standards. It is therefore possible for the galaxies' properties to change enormously with redshift and correspondingly hard to compare the current galaxy population with its progenitor population to interpret the number counts.

The situation is quite different in the near IR. In a 2.2-µm (K band) galaxy sample, we are usually seeing light from near-solar-mass stars whose lifetimes are comparable to the age of the galaxy. This means that evolutionary corrections are much smoother and can be more securely modeled. There is also the advantage that out to substantial redshifts the K band samples the relatively well-understood optical portion of the galaxy spectrum, so other uncertainties in the modeling are removed or minimized. Finally, because the optical and near-IR spectrum is generally much flatter than the UV portion, galaxies brighten slightly with increasing redshift in the near IR as opposed to rapidly dimming in the optical, and galaxies remain much brighter to large redshift. This last effect is important because galaxy counts that reach faint enough limits to break through and see the whole-galaxy-occupied cosmological volume contain information about its shape and size. However, the most powerful aspect of the 2.2-µm selection is that k corrections are very similar for all types of galaxies over a wide range of redshift (Fig. 1), in sharp contrast to the situation at optical wavelengths. Consequently, selecting galaxies by IR magnitude provides a relatively uniform sample of galaxy types regardless of redshift. This allows us to avoid having to model the absolute magnitude dependence of the local galaxy type mix or deal with the corresponding uncertainties in the local luminosity function for different galaxy types.

The current status of the differential galaxy counts in K is shown in Fig. 2. To K = 17, the counts are best fitted by a slightly super-Euclidean form log(N/0.12) = 0.63(K - 10), but above K = 17 the slope flattens significantly, dropping to log(N/1.25 x 10^3) = 0.26(K - 22.5). At the faintest counts the deviation from the bright-end slope is very large.

The turnover of the counts at K = 17 is expected; it is a consequence of the redshifts approaching z = 1 and the volume element departing from the Euclidean form. We show some simple models in Fig. 3 that assume an invariant Schechter luminosity function to z = 5, with p = 1.1 x 10^-3 Mpc^-3, a = -1, and K_S = -25.1 [1 megaparsec (Mpc) = 3.09 x 10^24 m]. These parameters are taken from Mobasher et al. (9) but with p raised by a factor of 1.6 to allow for the fact that, in the blue, the Mobasher counts are low compared with the much larger automated plate measuring (APM) survey (10). We have also shown the same models computed with the expected passive luminosity evolution modeled as dM_K/d ln (t = -0.6, which is at the low end of the values given by Tinsley and Gunn (11). As we have stated in previous reviews, these luminosity evolution models give a reasonable approximation to the faint-end counts for open and flat
models, but they do not predict another effect, which is that the $(B-K)$ colors, after initially becoming redder at faint magnitudes, become bluer after $K = 17$, as is shown in Fig. 4. At brighter magnitudes, the $K$ band selection predominantly picks out early-type galaxies, but by $K = 20$ the average galaxy has the color of an irregular. However, it is when we turn to the spectroscopy of the $K$-selected samples that the problems with conventional luminosity evolution models become blatant.

**K Band Spectroscopic Samples**

A.S., E. M. Hu, and L.L.C. (unpublished results) provide a sample of 128 spectroscopic redshifts for a series of $K$ magnitude-selected samples. The distribution in $K$ magnitude is roughly constant at about 20 redshifts per magnitude bin from $K = 13$ to $K = 20$, and the samples are essentially complete to $K = 19$ and about 70% complete between $K = 19$ and 20; the unpublished results of A.S., E. M. Hu, and L.L.C. give color-estimated redshifts for the remaining 11 galaxies in the faintest bins. We have combined this data with the $K$ band magnitudes of Mobasher et al. (2) for the Durham–Anglo–Australian Redshift Survey (DARS) spectroscopic sample of 91 galaxies, which is complete to approximately $K = 12.5$.

The redshift distribution of the galaxies at faint $K$ magnitudes ($K = 18-20$) is shown in Fig. 5 Top; the shaded region shows the galaxies with spectroscopic redshifts and the open region shows those with color-estimated redshifts. The median redshift is 0.588 in this bin for 42 galaxies, and there are only a small number of $z > 1$ or possible $z > 1$ galaxies. There are no other $K$-selected samples to compare with, but we can construct from the data complete samples in the optical and

**Fig. 4.** A plot of the $B-K$ color as a function of $K$ magnitude for the Mobasher et al. (2) data and the four Hawaii surveys. The dots represent individual galaxies. The horizontal lines are the median $B-K$ for each bin, plotted with 1σ error bars based on the median sign test. The solid lines are predictions for unevolving galaxies, with ellipticals at the top, $Sb$ in the middle, and $Im$ at the bottom.

**Fig. 5.** Histograms of redshift distributions for $K = 18–20$ (Top), $I < 22$ (Middle), and $B = 23–24$ (Bottom). (Top) Galaxies with spectroscopic redshifts are shaded, and the remaining open region shows those with color-estimated redshifts. (Middle and Bottom) For the $I$ and $B$ samples, we compare with samples given by Hammer et al. (12) and by Allington-Smith et al. (13), respectively (dotted lines).
compare these with other samples that are now becoming available. For example, Hammer et al. (12) have presented a sample of 47 galaxies with I < 22, which has a median redshift of 0.575, which can be compared with the parallel data for 129 galaxies in the present sample, normalized by the area coverage as a function of $I$ magnitude. The median redshift in the Hawaii sample is 0.500. In Fig. 5 Middle, we compare the redshift distribution for 37 $B = 23-24$ galaxies with early results from Ellis and co-authors (13) on 12 galaxies. Again the agreement is good.

We show a magnitude–redshift diagram for the $K$ sample in Fig. 6 Left; solid symbols denote spectroscopic redshifts and crosses denote color-estimated redshifts. The information is summarized in Fig. 6 Right, where we plot the median redshift versus average $K$ magnitude in the bin. Error bars are 68% confidence limits computed using the median sign method. At brighter magnitudes, the data fits a Hubble law rather precisely. Indeed, for $K = 10-15$, a fit to a power law of the form distance $\propto z^\beta$ gives 98% confidence limits on $\beta$ of 0.93–1.07. The solid ($q_0 = 0.5$) and dashed ($q_0 = 0.02$) lines in Fig. 6 Right show median redshift predictions for models in which the luminosity function is assumed invariant except for the $k$ correction to the rest-wavelength $K$ band, while the dashed and dotted line shows a model with a modest amount of luminosity evolution (brightening by 0.6 magnitudes by $z = 1$). At magnitudes fainter than 17–18, the data deviate significantly even from the no luminosity evolution predictions in the sense that there is negative evolution in the average galaxy luminosity with increasing redshift. We can read from Fig. 6 that a fraction of a magnitude of dimming at a redshift of 1 is needed, with the exact value depending slightly on the cosmology.

We can show this result more formally by fitting the shape of the luminosity function. To do this, we have computed the cumulative rest-frame $K$ band light density as a function of absolute magnitude for the 109 galaxies with redshifts between 0.01 and 0.1 and the 112 galaxies with redshifts between 0.1 and 1.0. ($H_0$ is taken as 50 km s$^{-1}$ Mpc$^{-1}$). The median redshifts for the two samples are, respectively, 0.05 and 0.4. These cumulative light densities are shown in Fig. 7 for the $q_0 = 0.5$ and $q_0 = 0.02$ cases. Between the two redshift ranges, the asymptotic light density increase by a factor of 2.2 for $q_0 = 0.5$ and 1.9 for $q_0 = 0.02$. However, the exact value of the luminosity density increase is vulnerable to clustering effects, and the actual rise may be lower than this, since, as we mentioned previously, the Mobasher sample appears to be from an area of low density. If we renormalize this data to Loveday et al. (10), these values would drop by a factor of 1.5. By contrast, the average luminosity per galaxy has dropped. Using the Kolmogorov–Smirnov test applied to cumulative numbers versus absolute magnitude, corrected for relative volume as a function of absolute magnitude, we find that neither $q_0 = 0.02$ nor $q_0 = 0.5$ permits a redshift-invariant luminosity function at the
95% confidence level. We require that the population fades and that more faint galaxies are present, implying a significant decrease in the average luminosity per galaxy. By determining the luminosity function using the volume estimator (15) and applying the χ² test to a luminosity function of the form \((L/L_\odot)^\alpha \exp(-L/L_\odot))\), we find 95% confidence bounds for \(\alpha\) and \(K_\ast = -2.5 \log(L_\odot/L_\odot)\) that, in the redshift interval [0.01, 0.1], are nearly identical with those of Mobasher et al. (9), who find a best fit of \(\alpha = -0.8, K_\ast = -24.8\) using the same method. This is expected since the bulk of the data is common to the two analyses. For \(q_0 = 0.5\), we find best-fit solutions of \(\alpha = -0.7, K_\ast = -24.8\) at [0.01, 0.1] and \(\alpha = -1.2, K_\ast = -24.7\) at [0.1, 1]. Again, the possible importance of clustering in determining the exact values should be emphasized. The major point to take from the data is that \(K_\ast\) appears to be dimming with redshift, as opposed to the luminosity density, which is modestly increasing.

Thus the luminosity evolution models that fit the \(K\) band counts of \(IR\) Galaxy Counts are not consistent with the spectroscopic data—rather, we see increasing galaxy number density combined with fading magnitudes. For \(q_0 = 0.5\), we need a factor of 4 increase in density and about half a magnitude of dimming to \(z = 1\), whereas for \(q_0 = 0.02\), this becomes a factor of 2 and about 0.3 magnitudes of dimming. Flat models dominated by a cosmological constant give \(\phi_\ast\) and \(K_\ast\) constant—i.e., neither number density nor luminosity evolution, but this is not what is expected since galaxies should be brighter in the past. We can quantify this last point in the following way. Irrespective of merging, we can expect the light density of the galaxy population as a whole \((\lambda_\ast)\) to increase slowly with increasing \(z\) because of luminosity evolution. Following the Tinsley and Gunn (11) approximation for the passive evolution, we expect

\[
-\frac{d[2.5 \log(\lambda_\ast)]}{d \ln t} = 1.2 - 0.4x = S, \tag{1}
\]

where the stellar Initial Mass Function (IMF) is described by \(dN = Am^{-1}(1-x)dm\) and \(x\) is the age of the population at \(z\); we expect \(S\) to lie in the range 0.6–1.2 for a reasonable range of \(x\). The value of \(S\) can be measured by combining the counts and redshift information. A detailed description is given by A.S., E. M. Hu, and L.L.C. (unpublished results). If we include the Mobasher data, we obtain \(S = 1.5\) for both \(q_0 = 0.5\) and 0.02, but this is probably an overestimate because of the low Mobasher counts. If we simply exclude the Mobasher data, we obtain \(S = [1.0, 0.9]\) for \(q_0 = [0.5, 0.02]\), whereas if we renormalize the Mobasher points to Loveday we obtain \(S = [0.9, 0.7]\). By contrast, flat \(A\) models give values of 0.4 without Mobasher and 0.1 with renormalized Mobasher, which are too low. However, the more important point is that

the evolution in the \(K\) band light density is very much as expected from passive evolution with no new populations, and this strongly favors the hypothesis that the increase in number density is produced by breakup of existing galaxies.

Thus the data appear to be following the general trends of the merger theory. Detailed predictions have been given for idealized models of this type by Broadhurst et al. (16) and by Carleberg (14). The median redshift as a function of magnitude given by Carleberg agrees surprisingly well with the redshift–magnitude observations shown in Fig. 6, though it is clear from this figure that a somewhat lower rate of merging than that adopted by Carleberg would also provide an acceptable fit. Given the problems this type of model faces in being reconciled with local galaxy morphology and colors [e.g., Toth and Ostriker (17)], reducing the merger rate would be highly desirable.

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