A wide-field $K$–band survey – I. Galaxy counts in $B$, $V$, $I$ and $K$

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ABSTRACT

We present bright galaxy number counts measured with linear detectors in the $B$, $V$, $I$, and $K$ bands in two fields covering nearly 10 square degrees. All of our measurements are consistent with passive evolution models, and do not confirm the steep slope measured in other surveys at bright magnitudes. Throughout the range $16 < B < 19$, our $B$–band counts are consistent with the “high normalization” models proposed to reduce the faint blue galaxy problem. Our $K$–band counts agree with previous measurements, and have reached a fair sample of the universe in the magnitude range where evolution and K-corrections are well understood.

Key words: surveys – cosmology:observations – galaxies:evolution – galaxies:photometry – infrared:galaxies

1 INTRODUCTION

Observational studies of galaxy formation and evolution have advanced at an unprecedented pace in recent years. Two developments have played a key role: CCD imagery to very faint limits and the ability to measure redshifts for large samples at increasingly faint magnitudes. Progress to date has relied primarily on optical data, but it has been clear for some time that near-infrared observations are fundamental. Samples selected according to $K$–band flux are superior to the traditional $B$–selected samples in at least three respects: (i) In the infrared, K-corrections due to the redshift of the spectral energy distribution are smooth, well-understood, and nearly independent of Hubble type; the expected luminosity evolution is also smooth. (ii) At high redshift, the observer’s near-infrared samples the well-understood rest frame optical (dominated by long-lived, near-solar mass stars), while the optical band samples the poorly-understood rest frame ultraviolet (dominated by short-lived massive stars). (iii) Since near-solar mass stars make up the bulk of a galaxy, the absolute $K$ magnitude is a measure of the visible mass in a galaxy.

Deep photometric surveys of small areas measuring the number counts and colours of field galaxies have reached as faint as $K = 24$, (Gardner, Cowie & Wainscoat 1993; Cowie et al. 1994; Djorgovski et al. 1995,) and show significant amounts of galaxy evolution at high redshift. However, the interpretation of faint galaxy data (either counts or redshift distributions) hinges on an accurate statistical description of the local population of galaxies. Photometric and spectroscopic surveys of bright galaxies, covering an area large enough to average over the effects of large-scale structure, are required in order to obtain bright galaxy counts and colour distributions, measurements of the galaxy-galaxy correlation function, and the local luminosity function. In the $K$ band, the small size of infrared detectors and the corresponding small field of view available, has made it difficult in the past to image large areas. In the optical, much work has been done using photographic plates, but their non-linearity can introduce possible systematics in the photometry (Metcalf, Fong & Shanks 1995.)

We have imaged nearly 10 square degrees in two fields at high galactic latitude using a NICMOS3 detector in the near-infrared $K$ band, and a CCD camera in the optical $B$, $V$, and $I$ bands. Here, we present the galaxy number counts. In a companion paper (Baugh et al. 1996, Paper II) we present the galaxy correlation function. Our $K < 15$ photometric catalog has been used to select galaxies for spectroscopic follow-up, and future papers in this series will present the $K$–band galaxy luminosity function, the galaxy redshift and colour distributions, and a discussion of the star counts and colour distribution. One of our fields, centered on the north ecliptic pole, is ideally situated for viewing by
satellites in polar orbits, and has been the subject of deep IRAS and ROSAT observations.

2 THE DATA

We have imaged 9.84 square degrees in the $K$-band with a 256$^2$ HgCdTe NICMOS3 detector, and in the $B$, $V$, and $I$ bands with a 2048$^2$ CCD camera. The $K$-band observations were made in 1994 June with the IRIM camera on the Kitt Peak National Observatory 1.3m telescope. On this telescope, the IRIM camera has 1.96′′ pixels and an 8.36′′ field of view. Each point was observed with at least two 60sec exposures, reaching a 5σ galaxy detection depth of $K = 15.6$ in a 10′′ circular aperture. The 3σ surface brightness limit of our images is $K = 18.5$ mag arcsec$^{-2}$. The $B−$, $V−$, and $I−$band observations were made in 1995 June with the T2KA camera on the KPNO 0.9m telescope. On this telescope, the T2KA CCD has 0.68′′ pixels with a 23.2′′ field of view. Each point in each filter was observed with a 300sec exposure, and the images reach a 5σ detection depth of $B = 21.1$, $V = 20.9$, and $I = 19.6$ in a 10′′ circular aperture. The 3σ surface brightness limit is 24.0, 23.8, and 22.5 mag arcsec$^{-2}$ for $B$, $V$, and $I$ respectively. The location of the two fields were selected randomly, that is, without regard to the presence or absence of any known objects. The field centers are at RA 14h15m, Dec +00 and RA 18h00m, Dec +66; galactic latitudes +55 and +30 respectively. One of our fields has a nearby rich galaxy cluster within it, and to avoid biasing the galaxy counts, we have removed all objects within 1 degree radius of the central galaxy of this cluster. Thus the effective area for the counts presented here is 8.54 square degrees.

Table 1. The galaxy number counts

| Filter | Mag | Raw N | $\log(N)$ | $\sigma_{\text{high}}$ | $\sigma_{\text{low}}$ |
|--------|-----|-------|-----------|-------------------|-------------------|
| $K$    | 10.25 | 1 | -0.630 | 0.519 | 0.762 |
|        | 10.75 | 1 | -0.630 | 0.519 | 0.762 |
|        | 11.25 | 4 | -0.028 | 0.253 | 0.283 |
|        | 11.75 | 13 | 0.484 | 0.134 | 0.139 |
|        | 12.25 | 22 | 0.712 | 0.101 | 0.103 |
|        | 12.75 | 33 | 0.888 | 0.082 | 0.083 |
|        | 13.25 | 66 | 1.189 | 0.057 | 0.057 |
|        | 13.75 | 138 | 1.510 | 0.039 | 0.039 |
|        | 14.25 | 273 | 1.806 | 0.027 | 0.027 |
|        | 14.75 | 642 | 2.177 | 0.018 | 0.018 |
|        | 15.25 | 1290 | 2.480 | 0.012 | 0.012 |
|        | 15.75 | 2600 | 2.786 | 0.009 | 0.009 |
| $I$    | 12.25 | 2 | -0.329 | 0.365 | 0.451 |
|        | 12.75 | 1 | -0.630 | 0.519 | 0.762 |
|        | 13.25 | 6 | 0.148 | 0.203 | 0.219 |
|        | 13.75 | 11 | 0.411 | 0.147 | 0.153 |
|        | 14.25 | 23 | 0.731 | 0.099 | 0.101 |
|        | 14.75 | 26 | 0.785 | 0.093 | 0.094 |
|        | 15.25 | 63 | 1.169 | 0.058 | 0.058 |
|        | 15.75 | 95 | 1.347 | 0.047 | 0.047 |
|        | 16.25 | 198 | 1.666 | 0.032 | 0.032 |
|        | 16.75 | 398 | 1.970 | 0.022 | 0.022 |
|        | 17.25 | 644 | 2.179 | 0.017 | 0.018 |
|        | 17.75 | 1190 | 2.445 | 0.013 | 0.013 |
| $V$    | 12.25 | 1 | -0.630 | 0.519 | 0.762 |
|        | 12.75 | 1 | -0.630 | 0.519 | 0.762 |
|        | 13.25 | 6 | 0.148 | 0.203 | 0.219 |
|        | 13.75 | 11 | 0.411 | 0.147 | 0.153 |
|        | 14.25 | 5 | 0.069 | 0.224 | 0.246 |
|        | 14.75 | 6 | 0.148 | 0.203 | 0.219 |
|        | 15.25 | 14 | 0.516 | 0.129 | 0.133 |
|        | 15.75 | 25 | 0.768 | 0.095 | 0.096 |
|        | 16.25 | 48 | 1.051 | 0.067 | 0.067 |
|        | 16.75 | 83 | 1.289 | 0.050 | 0.050 |
|        | 17.25 | 142 | 1.522 | 0.038 | 0.038 |
|        | 17.75 | 265 | 1.824 | 0.026 | 0.027 |
|        | 18.25 | 454 | 2.027 | 0.021 | 0.021 |
|        | 18.75 | 760 | 2.254 | 0.016 | 0.016 |
| $B$    | 12.25 | 1 | -0.630 | 0.519 | 0.762 |
|        | 12.75 | 3 | -0.153 | 0.295 | 0.341 |
|        | 14.25 | 2 | -0.329 | 0.365 | 0.451 |
|        | 14.75 | 6 | 0.148 | 0.203 | 0.219 |
|        | 15.25 | 6 | 0.148 | 0.203 | 0.219 |
|        | 16.25 | 20 | 0.671 | 0.106 | 0.109 |
|        | 16.75 | 26 | 0.785 | 0.093 | 0.094 |
|        | 17.25 | 56 | 1.118 | 0.062 | 0.062 |
|        | 17.75 | 117 | 1.438 | 0.042 | 0.042 |
|        | 18.25 | 188 | 1.644 | 0.033 | 0.033 |
|        | 18.75 | 323 | 1.879 | 0.025 | 0.025 |
|        | 19.25 | 509 | 2.076 | 0.020 | 0.020 |
|        | 19.75 | 901 | 2.324 | 0.015 | 0.015 |

The raw number of galaxies in the 8.54 square degree area, and the $\log(N/\text{mag}/\deg^2)$. The high and low Poissonian errors are taken from the calculations of Gehrels (1986).

I < 18, V < 19 or B < 20 were confirmed by eye. The median Kron (1980) $r_1$ radius in the faintest magnitude bin on the optical images was typically 2.5″ for stars and 3.4″ for galaxies. The $I−K$ colour, in combination with the $B−I$ colour, is a good indicator of star/galaxy separation for all but the bluest objects. We found no large population
of compact objects with the colours of galaxies, nor did we find a large population of extended objects with the colours of stars. In the range $15 < K < 16$, star/galaxy separation was carried out on the basis of colour alone, using $V - I$ vs $I - K$ for the objects not detected in $B$.

The galaxy number counts are presented in Table 1 and the $K$--band counts are plotted in Figure 1. To expand the ordinate, we have subtracted the Euclidean slope $d\log(n)/dm = 0.6$. Alongside our data, we plot other existing bright $K$--band galaxy counts. For comparison we also show the predictions of a simple model, based upon the formulation of Yoshii & Takahara (1988), modified to include rest-frame and evolved spectral energy distributions from the GISSEL models (Bruzual & Charlot 1993; 1996 in preparation.) The model is similar to that used in Gardner (1996), except that we have used the revised version of the GISSEL models. For the current purposes, the main difference between the two versions is that rest frame optical-near infrared colours are redder. The solid lines include this passive evolution, while the dotted lines are no-evolution models, i.e. models that include only the cosmological geometry and K-corrections. The dashed line is a “local-underdensity” model proposed by Huang et al. (1996) and is discussed below. To construct the models we adopted the $b_j$ type-independent luminosity function of Loveday et al. (1992), converted to type-dependent luminosity functions in other filters through rest frame colours. The normalization of the models was determined with a least-squares fit of the passive-evolution flat universe model to our data.

Figure 1 shows our $I$--band galaxy counts, again with the Euclidean slope subtracted, together with other existing counts converted to the Kron-Cousins $I$ band which we used. Figure 3 shows our $V$--band galaxy counts and Figure 4 our $B$--band galaxy counts.

3 DISCUSSION

The $K$--band galaxy counts presented in Table 1 and Figure 1 show remarkable consistency with the counts of Huang et al. (1996), which were also based upon $K$--band observations of approximately 10 square degrees. While one of us (JPG) is also a co-author of that paper, the two data sets were collected, reduced and analyzed independently, and there is no overlap in area between the two surveys. The consistency of the two results indicates that both surveys represent a fair sample of the universe, so the bright $K$--band galaxy counts and their normalization are no longer a subject of debate.

Our counts in the region $13 < K < 15$ are within $1\sigma$ of the Huang et al. (1996) counts in each magnitude bin. Nevertheless, we measure a shallower slope. The slope of our counts is $0.627 \pm 0.010$, consistent with the flat-universe passive evolution model plotted in Figure 1. Thus our data do not support the conclusion of Huang et al. (1996) that a model with a steep slope is required to fit the bright $K$--band number counts. The value of the normalization, $\phi^* = 1.50 \times 10^{-2} h^3 Mpc^{-3}$, (for $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$) inferred from our counts is higher than the value in the Loveday et al. (1992) luminosity function converted to the $K$--band. This comparison, however, is uncertain because the transformation from the $b_j$-band luminosity function to a $K$--band luminosity function is very model dependent. The model $K^*$ depends strongly on the assumed rest-frame
colours and the 3 parameters of the Schechter (1976) luminosity function are strongly correlated. Neither of the two existing measurements of the $K$-band luminosity function surveyed enough galaxies to accurately constrain $\phi^*(r)$ (Mobasher, Sharples & Ellis 1993; Glazebrook et al. 1995). In the absence of an accurate measurement of the joint $[B,K]$ luminosity function, it is difficult to determine the consistency of the normalization of number count models in different filters. For this reason, we have normalized the models plotted in each of the figures to our data.

To fit the bright $K$-band number counts without passive evolution, Huang et al. (1996) have proposed that the local universe is underdense by a factor of 2. They have constructed a heuristic model in which this underdensity smoothly damps out by $z \approx 0.2$. This model is unphysical and, as they stress, the number counts alone do not contain enough information to constrain its specifics. Maddox et al. (1990) measured a steep slope in the bright $B$-band number counts and a local underdensity has also been proposed to explain this slope (Shanks 1990; Metcalfe et al. 1991). We plot the model of Huang et al. (1996) in Figure 3 (with their normalization) as a dashed line. This model does not fit our galaxy counts.

The $I$-band galaxy counts are presented in Table 1 and Figure 2. We used the Kitt Peak standard $I$ filter, corrected to the Kron-Cousins standard stars of Landolt, (1983; 1992). Also plotted in Figure 2 is a compilation of $I$-band counts, converted to Kron-Cousins $I_{pc}$, taken from the Canada-France Redshift Survey (Le Fevre et al. 1995, hereafter CFRS) and the WF/PC Medium Deep Survey counts of Casertano et al. (1995), (hereafter MDS). The latter were converted using $I_{pc} = I_{785} + 0.16 \times (V_{555} - I_{785})$ and $(V_{555} - I_{785}) = 1.6$ (Edvardsson & Bell 1989). While there are no other measurements of the $I$-band number counts as bright as ours, the faint end of our counts are consistent with the CFRS counts. They are not, however, consistent with the MDS counts, which are a factor of 1.5 higher. The MDS measurements are based upon pre-refurbishment WF/PC images. Casertano et al. (1995) found that the median half-light radius of their galaxies was $0.3''$, so star/galaxy separation based upon morphology alone would be very difficult. They ascribe the excess in their number counts to inaccurate star/galaxy separation in the ground-based data. However, as noted above, our star/galaxy separation is based upon morphology and colour, and we do not find a large population of compact objects with the colours of galaxies. In addition, the CFRS collaboration obtained spectroscopy of one sixth of the objects in their sample, without regard to morphology, and also did not find a large population of compact galaxies. The excess in the MDS counts is most likely due to errors in the photometry of the WF/PC images introduced in the deconvolution process.

The $V$-band galaxy counts are presented in Table 2 and Figure 2. We used the Kitt Peak standard $V$ filter, corrected to the Johnson $V$ standard stars of Landolt, (1983; 1992). There are only two other measurements of the $V$-band number counts, by Casertano et al. (1995) (MDS), and by Driver et al. (1994). $V_{555}$ is approximately equal to Johnson $V$ for the galaxies in these samples, so we have applied no correction. The MDS $V$ counts again show an excess over the faint end of the counts presented here.

The $B$-band galaxy counts are presented in Table 3 and Figure 4. We used the Kitt Peak standard $B$ filter, corrected to the Johnson $B$ standard stars of Landolt, (1983; 1992). The $B$ counts have been measured in many surveys, but this is the first time that $B$ counts at $B < 20$ have been obtained with a CCD camera, rather than with non-linear photographic plates. While our area is much smaller than other surveys, and our statistical error is higher, our counts are far less likely to suffer from systematic effects in the photometry. In Figure 4 we have plotted $b_J$ counts, converted to the Johnson $B$-band, from the APM survey of Maddox et al. (1990) (hereafter APM), and from the MAMA survey of Bertin & Dnnefeld (1996).

The APM counts show the steep slope at the bright end mentioned earlier. These authors interpreted the data as revealing a large (and unexpected) amount of luminosity evolution at low redshifts ($z < 0.1$). Other workers have attributed this steep slope to a local underdensity of galaxies (Shanks 1990; Metcalfe et al. 1991), to a selection effect against low surface brightness galaxies (McGaugh 1994; Ferguson & McGaugh 1995), or to systematics in the photometry (Metcalfe et al 1995). The slope measured in the APM data at $16 < B < 19$ is 0.59, while a linear fit to our data in this same range of magnitudes gives a slope of 0.50 $\pm$ 0.03. Our measured slope is consistent with passive evolution models, which have slopes of 0.52 and 0.51 for $q_0 = 0.5$ and 0 respectively, and agrees with that of Bertin & Dnnefeld (1996), who surveyed 145 square degrees using individually calibrated Schmidt plates. We have normalized the flat-universe passive-evolution model with a least-squares fit to our data. This normalization is equivalent to using a Schechter luminosity function with $b_J^* = -19.50 + 5 \log(h)$ and $\alpha = -0.97$, as measured by Loveday et al. (1992), but with $\phi^* = 2.02 \times 10^{-2} h^3 Mpc^{-3}$, a normalization that is a factor of 1.44 times higher than that measured in the Stromlo-APM survey (Loveday et al. 1992.) High normalization models have been proposed to reduce the excess of
faint blue galaxies that has been seen in deep photometric surveys (for a review, see Metcalfe et al. 1996), and to fit the WFPC2 Medium Deep Survey results (Glazebrook et al. 1995; Driver et al. 1995). The sensitivity of our survey to low surface brightness galaxies, and the effects of clustering on the errors of the number counts will be discussed elsewhere (Gardner et al., in preparation).

4 CONCLUSIONS

We have presented bright galaxy number counts measured with linear detectors in the $B$, $V$, $I$, and $K$ bands in two fields totalling nearly 10 square degrees. All of our measurements are consistent with passive evolution models. Our counts do not exhibit the steep slope measured in other surveys, either in the $K$– or $B$– bands, and so do not support earlier interpretations that required a large amount of luminosity evolution at low redshift. We also do not find evidence of a large underdensity in the local universe, unless it is a phenomenon occurring exclusively in the South Galactic Pole region. (Both of our fields are North of the Galactic Plane.) Our data are consistent with the conclusions of Metcalfe et al. (1995) that the steep slope measured previously in the bright $B$–band number counts is most likely due to systematic errors in the non-linear photometry of photographic plates. Our $B$–band counts support the high normalization models, based upon a local $\phi$ approximately 1.4 times higher than that measured by Loveday et al. (1992). Our $K$–band counts are consistent with previous measurements, and have reached a fair sample of the universe in the region where evolution and K-corrections are well understood.

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