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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 deg^2. 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 – galaxies: evolution – cosmology: observations – 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 (Metcalfe, Fong & Shanks 1995).

We have imaged nearly 10 deg^2 in two fields at high galactic latitude using a NICMOS3 detector in the near-infrared *K* band, and a CCD camera in the *B*, *V* and *I* optical bands. Here, we present the galaxy number counts. In a companion paper (Baugh et al. 1996, hereafter Paper II) we present the galaxy correlation function. Our $K < 15$ photometric catalogue 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, centred 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.

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2 THE DATA

We have imaged 9.84 deg^2, 256 × 256 pixel in the K band with an HgCdTe NICMOS3 detector, and 2048 × 2048 pixel in the B, V and I bands with a CCD camera. The K-band observations were made in 1994 June with the IRIM camera on the Kitt Peak National Observatory (KPNO) 1.3-m telescope. On this telescope, the IRIM camera has 1.96-arcsec pixels and an 8.36-arcmin field of view. Each point was observed with at least two 60-s exposures, reaching a 5σ galaxy detection depth of $K = 15.6$ in a 10-arcsec circular aperture. The 3σ surface brightness limit of our images is $K = 15.6$ in a 10-arcsec 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 0.9-m telescope. On this telescope, the T2KA CCD has 0.68-arcsec pixels with a 23.2-arcmin field of view. Each point in each filter was observed with a 300-s exposure, and the images reach a 5σ detection depth of $B = 21.1$, $V = 20.9$ and $I = 19.6$ in a 10-arcsec 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 locations of the two fields were selected randomly, that is, without regard to the presence or absence of any known objects. The field centres are at RA 14^{h}15^m, Dec. +00° and RA 18^{h}00^m, 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° radius of the central galaxy of this cluster. Thus the effective area for the counts presented here is 8.54 deg^2.

Image reduction will be described in detail elsewhere (Gardner et al., in preparation), but mainly follows the techniques described by Gardner (1995). Briefly, the K-band images were dark-subtracted, flattened with domeflats and median sky-subtracted, and large-scale gradients were removed with a large (2 arcmin) median filter. The optical images were bias-subtracted and flattened with twilight flats. In addition, the I-band images were flattened with median sky flats. Object identification on the optical images was performed with the SEXTRACTOR program (Bertin & Arnouts 1996), using a 3σ threshold. Deblending was performed with a multithresholding approach, and integrated pixels were assigned to each object. Magnitudes are the SEXTRACTOR mag_best, which is the flux in an elliptical aperture at 2.5 times the Kron (1980) radius along the semi-major and semiminor axes for isolated objects, and a corrected isophotal magnitude when deblending was required. K-band photometry was carried out using 10-arcsec apertures on all identified I-band objects. The aperture magnitudes were deblended by assigning pixels by hand, and were corrected to total magnitudes using the curve of growth measured in the I band. Colours for all objects were measured within 5-arcsec circular apertures in the optical, and within 6 × 6 arcsec^2 apertures in $I-K$.

Star/galaxy separation is critical at these magnitudes, and was carried out using a combination of morphology on the optical images and the colour criterion discussed by Gardner (1995). The seeing of the optical images varied through the observing run between 2 and 3 pixel, or 1.3 < FWHM < 2.0 arcsec. All identified galaxies with $K < 15$, $I < 18$, $V < 19$ 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 arcsec for stars and 3.4 arcsec 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

Table 1. The galaxy number counts.

Filter	Mag	Raw N	$log(N)$	σ_{high}	σ_{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	2609	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
	13.25	1	-0.630	0.519	0.762
	13.75	1	-0.630	0.519	0.762
	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	285	1.824	0.026	0.027
	18.25	454	2.027	0.021	0.021
	18.75	766	2.254	0.016	0.016
B	12.25	1	-0.630	0.519	0.762
	14.25	3	-0.153	0.295	0.341
	14.75	2	-0.329	0.365	0.451
	15.25	6	0.148	0.203	0.219
	15.75	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-deg^2 area, and the log (N mag^{-1} deg^{-2}). The high and low Poissonian errors are taken from the calculations of Gehrels (1986).

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 $V-I$ versus $I-K$ for the objects not detected in B.

The galaxy number counts are presented in Table 1, and the K-band counts are plotted in Fig. 1. To expand the ordinate, we have subtracted the Euclidean slope $\mathrm{d}\log(n)/\mathrm{d}m = 0.6$. 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; Bruzual & Charlot, 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. 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.

Fig. 2 shows our I-band galaxy counts, again with the Euclidean slope subtracted, together with other existing counts converted to the Kron–Cousins I band that we used. Fig. 3 shows our V-band galaxy counts and Fig. 4 our B-band galaxy counts.

3 DISCUSSION

The K-band galaxy counts presented in Table 1 and Fig. 1 show remarkable consistency with the counts of Huang et al. (1996), which were also based upon K-band observations of approximately 10 deg^2. While one of us (JPG) is also a co-author of that paper, the two data sets were collected, reduced and analysed 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 1σ 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 ± 0.010, consistent with the passive-evolution flat universe model plotted in Fig. 1. Thus our data do not require a model with a steep slope to fit the bright K-band number counts. The value of the normalization, $\phi^* = 1.50 \times 10^{-2}\, h^3$ Mpc^{-3} (for $H_0 = 100\, h$ km s^{-1} Mpc^{-1}), inferred from our counts is higher than the value in the

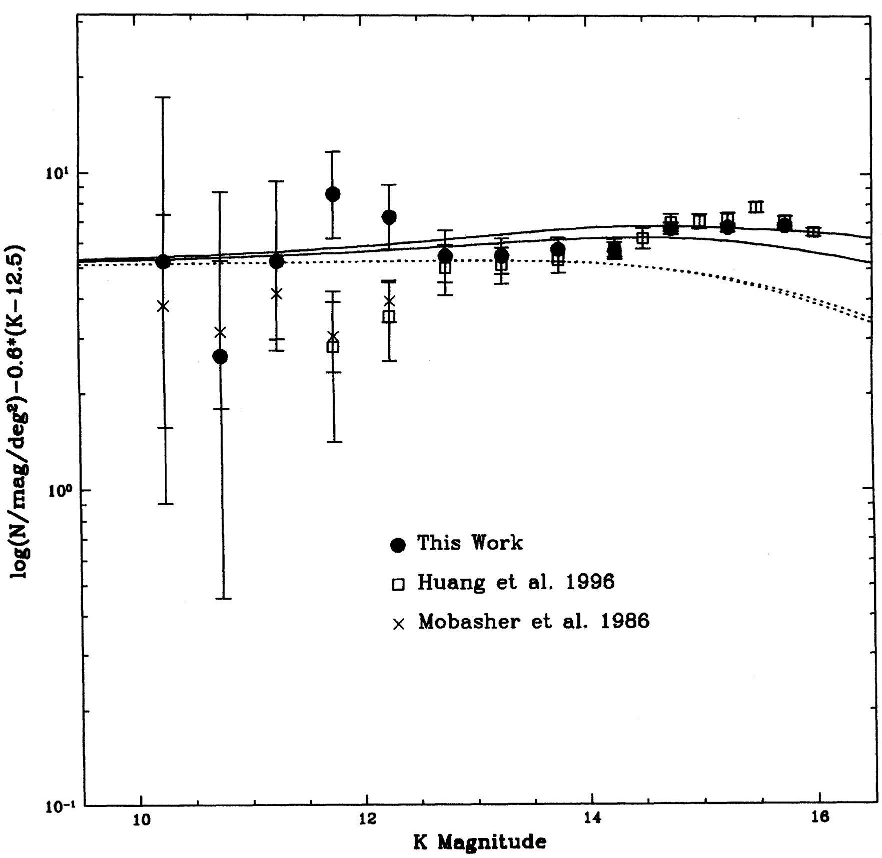

Figure 1. The K-band galaxy counts. The Euclidean slope, $\mathrm{d}\log(n)/\mathrm{d}m = 0.6$, has been subtracted in order to expand the ordinate. The models plotted are no-evolution (dotted line) and passive-evolution (solid line), in an open universe (the two middle lines at faint magnitudes) and in a closed universe. The data have Poissonian errors plotted, as given in Table 1.

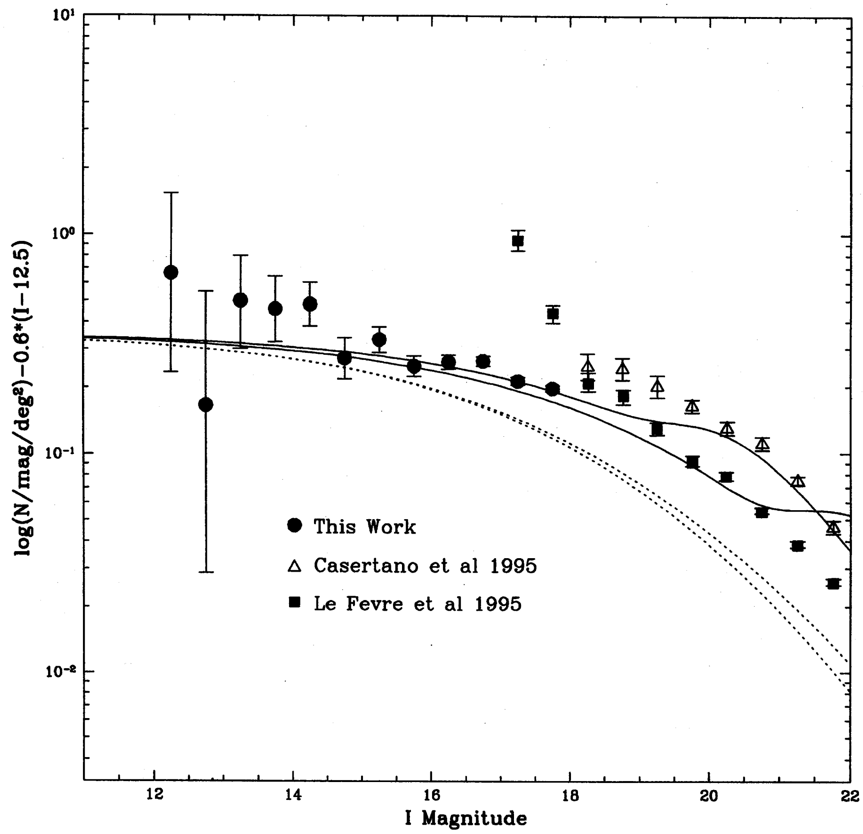

Figure 2. The *I*-band number counts. The models plotted are as in Fig. 1. All counts have been converted to I_{KC} as discussed in the text. The Medium Deep Survey counts of Casertano et al. (1995) show an excess over our counts and over those of CFRS.

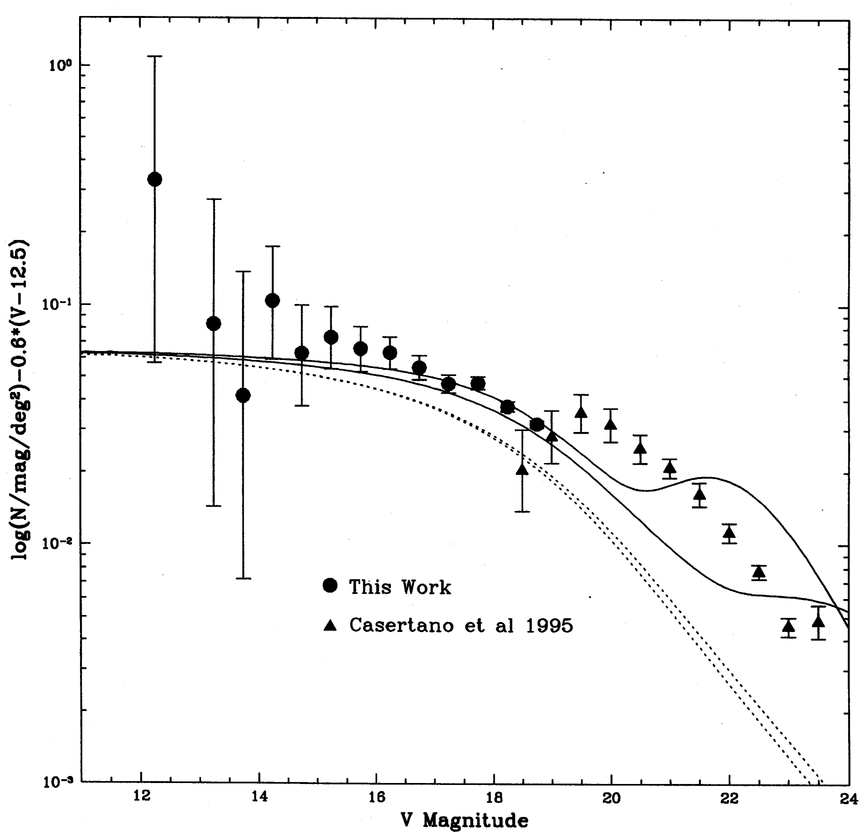

Figure 3. The *V*-band number counts. The models plotted are as in Fig. 1.

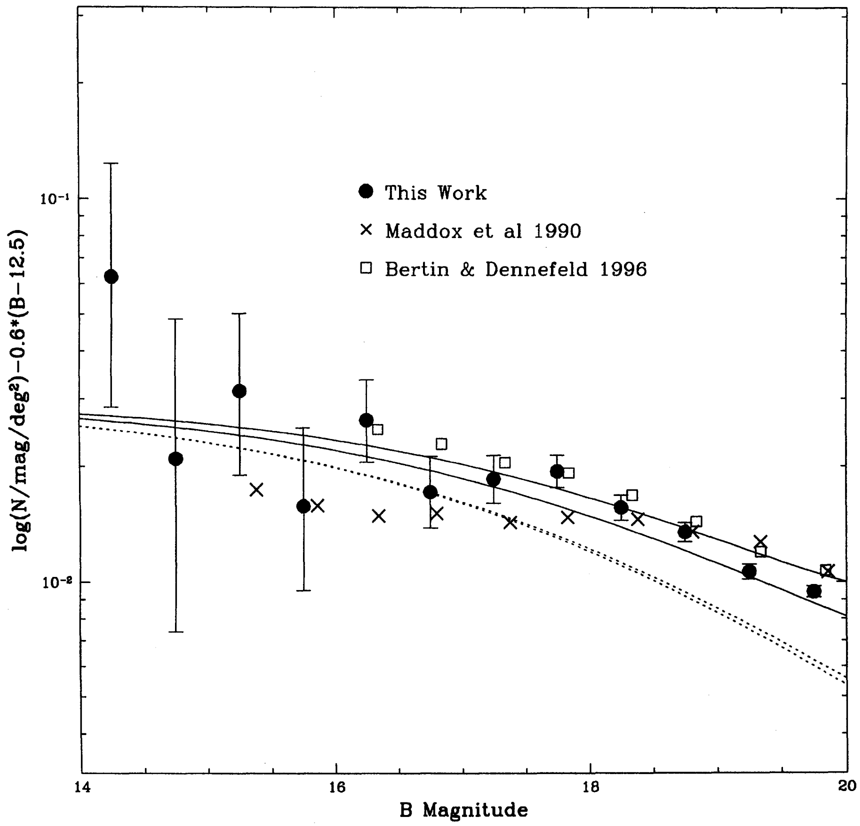

Figure 4. The B-band number counts. The models plotted are as in Fig. 1. All counts have been converted to Johnson B as discussed in the text. Our counts show a shallower slope than the APM counts of Maddox et al. (1990), and are consistent with passive-evolution models.

Loveday et al. (1992) luminosity function converted to the K band. This comparison is, however, 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 three 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 ϕ^* (Mobasher, Sharples & Ellis 1993; Glazebrook et al. 1995). In the absence of an accurate measurement of the bivariate [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.

The I-band galaxy counts are presented in Table 1 and Fig. 2. We used the Kitt Peak standard I filter, corrected to the Kron–Cousins standard stars of Landolt (1983, 1992). Also plotted in Fig. 2 is a compilation of I-band counts, converted to Kron–Cousins I_{KC}, 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 $I_{KC} = I_{785} + 0.16(V_{555} - I_{785})$ 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 arcsec, 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 1 and Fig. 3. 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 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 against show an excess over the faint end of the counts presented here.

The B-band galaxy counts are presented in Table 1 and Fig. 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 Fig. 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 & Dennefeld (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 ± 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 & Dennefeld (1996), who surveyed 145 deg^2 using individually calibrated Schmidt plates. We have normalized the passive-evolution flat universe 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 Wide Field and Planetary Camera 2 (WFPC2) Medium Deep Survey results (Glazebrook et al. 1995; Driver, Windhorst & Griffiths 1995). The sensitivity of our survey to low surface brightness galaxies and the effects of clustering on the numbers in the error 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 deg^2. 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 photometric plates. Our B-band counts support the high-normalization models, based upon a local ϕ^* 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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