THE HAWAII K-BAND GALAXY SURVEY. II. BRIGHT K-BAND IMAGING

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ABSTRACT

We present the results of a wide-field K-selected galaxy survey with complementary optical I- and B-band imaging in six fields with a total coverage of 9.8 deg$^2$. The observations were carried out on the University of Hawaii 0.6 m and 2.2 m telescopes. The purpose of this survey is to study the properties of the local galaxies and explore the evolution of K-selected galaxies at low redshifts. Star-galaxy discrimination is performed using both galaxy color properties and object morphologies, and 6264 galaxies are found. This survey establishes the bright-end K-band galaxy number counts in the magnitude range $13 < K < 16$ with high precision. We find that our bright-end counts have a significantly steeper slope than the prediction of a no-evolution model, which cannot be accounted for by known observational or theoretical error. We argue also against the likelihood of sufficient evolution at such low redshifts to account for this effect; we describe an alternative picture in which there is a local deficiency of galaxies by a factor of 2 on scale sizes of around $300 \text{ h}^{-1} \text{ Mpc}$. Taken at face value, this would imply that local measurements of $\Omega_{\phi}$ underestimate the true value of the cosmological mass density by this factor and that local measurements of $H_0$ could be high by as much as 33%.

Subject headings: cosmology: observations — galaxies: photometry — galaxies: structure — infrared: galaxies — surveys

1. INTRODUCTION

Near-infrared galaxy surveys (Mobasher, Ellis, & Sharples 1986; Gardner, Cowie, & Wainscoat 1993; Glazebrook et al. 1994; Cowie et al. 1994; McLeod et al. 1995; Djorgovski et al. 1995) have provided extensive information on galaxy evolution. As noted by these studies, a near-infrared–selected galaxy sample may provide more advantages in studying galaxy evolution and cosmological geometry than an optically selected sample. Its insensitivity to transient bursts of star formation and its small K-corrections even at large redshift simplify our modeling of the galaxy number count–magnitude relation and can lead to a direct determination of galaxy evolution. The near-infrared K-correction is also insensitive to spectral type; thus, a near-infrared–selected sample is unbiased with respect to the mix of spectral type. This is very valuable in studying large-scale structure.

Because of the small format of the first-generation IR arrays, the early K-band surveys (Gardner et al. 1993; Glazebrook et al. 1994; Cowie et al. 1994) were mainly deep surveys over relatively small areas. After the Keck telescope became available, it became easier to conduct such pencil-beam deep K-band surveys (Djorgovski et al. 1995). Unlike the B-band number counts, which show a large excess over the no-evolution prediction for the faint-end counts, the K-band number counts established from these surveys do not show such a large excess. However, in order to draw conclusions on the nature of galaxy evolution in these deep samples, it is essential to have extensive knowledge of the local K-band luminosity function and the color distribution of a local K-selected sample, and there are few such samples available. The primary sample used as a local reference was one obtained by Mobasher et al. (1986). Their complete K-band sample to $K = 12$ was extracted from the B-selected sample. Later a K-band local luminosity function was constructed using this sample (Mobasher, Sharples, & Ellis 1993).

The recent development of large-format IR arrays such as the NICMOS ($256 \times 256$) and HAWAII ($1024 \times 1024$) HgCdTe devices has now made it possible to conduct a large field near-infrared survey. The Hawaii wide-field K-band survey aims to study the local galaxy properties in the near-infrared. With about 10 deg$^2$ coverage and a limiting magnitude of $K = 16$, the sample contains 6264 galaxies. This sample will allow us to determine the local galaxy density and the morphological mix of the K-selected local galaxy sample. The current availability of a multifiber spectrograph (Taylor 1994) also makes it possible to conduct redshift measurements effectively for our sample. Hence, using this sample we will eventually be able to construct a more precise K-band local luminosity function. In this paper, we will discuss the imaging and photometry of the survey and define a K-band galaxy number–magnitude relation to $K = 16$. We also apply the no-evolution model to the observed galaxy number–magnitude relation and discuss the distribution of the local K-selected galaxy density. In a future paper, we will analyze the morphological mix of the K-selected bright galaxy sample up to $K = 14$ (Huang & Cowie 1996).

2. OBSERVATION AND DATA ANALYSIS

2.1. Field Selection

The Hawaii wide-field K-band survey consists of two parts. The first part was done in two relatively small areas, totaling about 1.58 deg$^2$, to a magnitude limit of $K = 14.5$. This part of the survey yielded a relatively small sample whose redshifts could be measured easily. The data analysis and redshift measurement are given in Gardner (1992) and Songaila et al. (1994). We will reanalyze these data together with the second part of the survey.

The second part of the survey is designed to use the newly developed multifiber spectrograph (the 2DF) on the Anglo-
Australian Telescope (Taylor 1994) for follow-up redshift measurement. Four fields, named SA, SB, SC, and SD, were selected on the equator, so as to be observable from both Mauna Kea, Hawaii, and the AAO in Australia. These four fields avoid rich clusters and very bright stars. We also selected fields on which previous surveys have been carried out. Glazebrook et al. (1994) conducted a medium-deep K-band survey on the fields SA, SC, and SD with small sky coverage. The fields SC and SD are also sites of the Anglo-Australia Redshift Survey, each with a total of 14 deg$^2$ of coverage (Peterson et al. 1986). All four fields are at high galactic latitudes to avoid galactic extinction. After we trim those parts of the areas with insufficient signal-to-noise ratio (S/N), each field splits into two to four pieces and the total number of areas becomes 13. The positions and completeness limits in the K band are summarized in Table 1.

### 2.2. Observation and Data Reduction

The observations were carried out on the University of Hawaii telescopes on Mauna Kea, over more than 100 nights during the 1993–1995 period. The K-band images were taken using the 24 inch (60.96 cm) telescope with the NICMOS 1R camera (256 × 256 pixels). The field of view of the NICMOS camera on the 24 inch telescope is approximately 8', with a scale of 2.02 pix$^{-1}$. Each field was observed frame by frame in the declination direction to form a 1° strip, then each strip was stepped in the R.A. direction. The offset between frames in each strip is about 4', or half a field of view. Hence, a strip contains 16 images. The offset between each strip is also 4'. Therefore, each pixel was exposed four times in total, except those on the edges and corners which were exposed two times and one time, respectively. These edges are trimmed in the final mosaic frames. With a 2 minute exposure time for each single image, the final mosaic K-band image has an exposure time of 8 minutes. The advantage of this observational pattern is that bad pixels and cosmic rays are removed easily, as we form the final image by taking the median of the 4 counts on each pixel. Instead of using a standard K filter, we used the K$'$ filter (Wainscoat & Cowie 1992), which is slightly bluer than the standard K filter, to avoid the thermal IR emission. The K$'$ filter reduces significantly the sky background. The background of each frame with a 2 minute exposure time is still very high, on average 3000–5000 counts. The background also increases with air mass, so each observation was limited to an hour angle less than 2.5 hr. There are further advantages to the low air mass limitation: it ensures a uniform S/N throughout whole area, and it minimizes the zero-point problem due to different air masses in the final mosaic, since the magnitude difference for the background in our fields between zenith and hour angle of 2.5 hr is less than 0.01. The near-infrared standard stars were taken from the list of Elias et al. (1982), with K magnitudes of 6 < K < 9. We used a linear relation derived by Wainscoat & Cowie (1992) to transfer the K magnitudes of the standard stars to the K$'$ magnitudes. Since the linear dynamic range of each pixel in the NICMOS camera is up to 20,000 count rates, the exposure time must be short enough for the standard stars to prevent saturation. We took 5 s exposure time for our standard stars. The highest peak count rates of our standard stars are about 12,000.

The image processing for the near-infrared images is the same as that used in the Hawaii Deep Survey, described in Cowie et al. (1994). We would like to emphasize some important points here again. For the K-band images, the dark current is insignificant, and therefore it was not subtracted from each raw data frame. The flat field was created by using the high sky background of the raw data. Due to the variation of the sky OH emission, the sky flat field in K-band may change on timescales of 20–30 minutes (Glazebrook et al. 1994). Hence, for each raw K-band image, the flat field was generated by using a median filter of 10 nearby adjacent frames in the observation time sequence. Since the sky background is so high, the noise is then dominated by the background noise. The flat field generated from 10 raw frames should have a lower noise level than the expected final mosaic images, which are a median of only four raw images, so that the flat field created in this way does not contribute significant noise to the final image.

We were successful in obtaining B- and I-band photometry of the entire area reported in Table 1 covered by the K-band exposures. The observations in I and B bands were obtained primarily on the 88 inch (2.23 m) telescope with a Tek2048 CCD. Of the total area for which we obtained the B-band photometry, about 25% was observed with the 24 inch. The purpose of the optical imaging is to separate stars from galaxies in the color-color diagram, and to study the morphology of the K-selected galaxies. With a scale of 0.2' pixel$^{-1}$ and average seeing of 0.8', the I-band images have much higher spatial resolution than the K-band images. The field of view for the CCD images is about 7' at the 88 inch. The observing pattern for the optical observations is similar to that of the K-band observations. The effective exposure time is 2 minutes for the I- and B-band images taken on the 88 inch telescope, and 20 minutes for the B-band images taken on the 24 inch telescope.

The data reduction for the optical images follows standard procedures. Each raw data frame was bias subtracted and then divided by a flat field. The procedures for obtaining the flat fields for I- and B-band images are different. For the I-band images, the flat field was created in the same way as for the K-band images. Since the I-band sky background is also high and stable, a sky flat was used in the I-band image processing. Because of the extremely low sky background level in B band, a twilight flat field was used for the B-band images.

### Table 1

| Name   | $a$(1950) | $\delta$(1950) | $b$ | Area (deg$^2$) | $P_{16}$* |
|--------|-----------|----------------|-----|----------------|-----------|
| SSA13a | 13:10:01:7 | 43:00:33       | 74  | 0.84           | ...       |
| SSA17a | 17:04:59:8 | 43:59:35       | 37  | 0.74           | ...       |
| SA      | 22:42:57:6 | -00:28:12      | -49 | 0.46           | 0.97      |
|         | 22:41:20:9 | -00:27:40      | -49 | 0.15           | 0.97      |
|         | 22:39:10:8 | -00:29:23      | -49 | 0.84           | 0.72      |
| SB      | 03:43:32:3 | -00:30:21      | -41 | 0.34           | 0.92      |
|         | 03:38:57:7 | -00:29:40      | -41 | 1.63           | 0.92      |
|         | 03:43:55:0 | -00:26:49      | -41 | 0.14           | 0.70      |
|         | 03:42:39:8 | -00:29:19      | -41 | 0.35           | 0.72      |
| SC      | 10:41:23:8 | -00:27:46      | -49 | 1.72           | 0.96      |
|         | 10:43:29:9 | -00:28:49      | -49 | 0.30           | 0.90      |
| SD      | 13:41:56:3 | -00:25:49      | 60  | 0.82           | 0.96      |
|         | 13:37:58:9 | -00:25:46      | 60  | 0.74           | 0.96      |
|         | 13:43:11:8 | 00:28:52       | 60  | 0.32           | 0.96      |
|         | 13:42:10:2 | 00:28:56       | 60  | 0.42           | 0.96      |

*a $P_{16}$ is the recovery rate of a galaxy with K = 16.

b These two fields are from Gardner 1992 and Songaila et al. 1994 with completeness at K = 14.5.
The final registering of the \( K \)-band images is difficult. Due to the inaccurate pointing of the University of Hawaii 24 inch telescope, the offset between each neighboring frame needs to be determined precisely. Lack of bright stars and the high noise level in the primary frames can make this measurement difficult. We have developed the following method to cope with this problem. The offset between neighboring frames was measured by using bright stars in the overlapping area. Saturated stars were not used in measuring positions. For those frames with no usable bright stars but apparent faint objects above the noise, a cross-correlation function was used in the overlapping area to determine the offset. At this point, there were only 5\% of the frames left whose cross-correlation functions with their neighbor frames had S/Ns too low to determine the offset. The first mosaic was constructed without those frames. The position of each frame on the final mosaicked frame was calculated from its offsets to its neighbor frames. The count for each pixel of the final frame was the median of counts of the four exposures, except for those pixels on the edges. The S/N for those fully covered pixels increases by a factor of 2. We estimated roughly the position for the remaining frames by guessing their offsets to the neighbor frames, usually half the raw field of view as designed by our observing stepping pattern; then we cut out a similar field of view from the first-pass mosaic, where the composite S/N has generally been substantially improved over that of a single neighboring “raw” data frame, and then we ran a cross-correlation function with the corresponding frame to be incorporated into the final position. In this second pass, the peak of the cross-correlation function can be well determined, since one image has an improved S/N usually by a factor of \( 1@2 \). The position of this frame in the final composite, therefore, could be located. The frame was then incorporated into the composite mosaic. Before each frame is added to the composite mosaic, the peak of the cross-correlation function between this frame and the composite mosaic is measured again to suppress the growth of errors by random walks. This process was repeated until all the remaining frames that had been omitted from our first-pass composite mosaic were located. Before the final mosaic was generated, an air mass correction for extinction was applied to each of the original frames.

The registering of the optical images is much easier, since the effective exposure time for the \( I \)- and \( B \)-band observation results in images deep enough to have many usable stars. Therefore, the position of each CCD image can be determined precisely in the final mosaicked image. The \( K \) - and \( B \)-band images are fully registered to the \( I \)-band images. Due to the large size of the \( K \)-band images (\( \sim 2'02 \) pixel \(^{-1}\)), the position error of a star between the \( K \)-band image and optical images may be as large as \( 2'' \), though the position error between the \( I \)- and \( B \)-band images is much smaller. The final three-color images were cut into pieces, each with size \( 7.3 \times 7.3 \), for easy storage and further analysis.

2.3. Detection and Photometry

The object selection was carried out on the registered \( K \)-band images. \( I \)- and \( B \)-band counterparts can be located easily, allowing for positioning error, at the position at which the \( K \)-band objects are detected. Since the original low-resolution \( K \)-band images were registered to \( I \)-band images that had much smaller pixel scales, this procedure tends to smooth the \( K \)-band images, and no further smoothing is applied. For the University of Hawaii 24 inch telescope, there are many factors contributing to the image quality, such as dome seeing, inaccuracy of tracking, and wind shake. The width of the point-spread function (PSF) on \( K \)-band images is slightly larger than the pixel scale. Our detection procedure is similar to Tyson (1988). The criterion for identifying an object on the registered \( K \)-band images is that an object must cover an area of at least 12 arcsec\(^2\) down to a \( K \)-band surface brightness of 20 mag arcsec\(^{-2}\). This criterion is equivalent to having three connected pixels, each having counts higher than 3 \( \sigma \) on the \( K \)-band images.

The completeness of the sample was tested by using extensive Monte Carlo simulations. We first mimicked the noise according to the real images. Then five bright galaxies with different Hubble types were selected. After rescaling the counts of these galaxies by different factors, we added the simulated noise and ran the detection process to obtain the galaxy detectability as a function of magnitude. We found that, in each field, such functions vary slightly according to galaxy type. The sixth column of Table 1 gives the median recovery rate at \( K = 16 \) mag for each field, ranging from 70\% to 97\%.

The method of photometry is very important in analyzing our results, and therefore it should be treated very carefully. As many previous studies have indicated that, for a faint galaxy, its isophotal photometry is strongly dependent on redshift and hard to model, we have chosen to use aperture photometry. Because of the low spatial resolution in the \( K \)-band images and the large angular size of the bright galaxies, a large aperture is required. An 8" diameter aperture is adopted. This aperture magnitude is corrected to 20" diameter. For bright galaxies, specifically \( K < 13 \), their sizes are generally larger than 20", and corrections of aperture magnitudes for these galaxies are large and variable. For these galaxies, we used an isophotal magnitude measuring the isophotal magnitude to a surface brightness of 20 mag arcsec\(^{-2}\). Since these bright galaxies are local, there is little cosmological effect on their isophotal magnitudes.

Since stars and galaxies have different growth curves, their aperture magnitudes were corrected separately. First, we classified stars and galaxies by using their morphological indicators measured in the \( I \)-band images, which will be discussed in next chapter. Since a bright galaxy is more extended than a faint galaxy, we have to correct the magnitude differently according to its apparent magnitude. Then we divided galaxies and stars into bins according to their magnitudes using a 0.2 mag bin size. The growth curves were measured by using well-isolated stars and galaxies in each of the bins. The star and galaxy corrections in each bin were made from the median of these stellar and galactic growth curves. Because of the variation of the PSF, the corrections for each field are treated separately. Figure 1 is an example from one field, and it shows that the corrections for galaxies are a function of the apparent magnitude for galaxies. The corrections for stars are not a function of aperture magnitude, since they have the same PSF at all magnitudes.

For \( I \)- and \( B \)-band photometry of the \( K \)-selected sample, the magnitude was measured with the same procedures as for the \( K \) magnitudes centered on the position of the objects in that color. Since we have a large aperture (8"), it makes almost no difference whether we measure the optical magnitude at the position of the \( K \)-selected object or the best
optical position. If more than one object was found close to the $K$-selected object within $2^\prime$, the one closest to the position of the $K$-selected object was used. If nothing was found, a $3\sigma$ upper limit was adopted. The optical photometry was performed in exactly the same way as the $K$-band photometry except that on the $I$-band images, an extra parameter, the fourth moment of the radius, was measured on each object for morphological classification. This parameter is defined as

$$r_4 = \frac{\int f(r)r^4 \, dr}{\int f(r)r^2 \, dr}$$

where $f(r)$ is the flux and $R$ is the maximum radius for the integral. If $R$ is too large, $r_4$ can be dominated by noise. We found empirically that the noise can be minimized for $r_4$ when $R = 3^\prime$.

The same procedure of detection and photometry was run again through the $B$-band images to obtain the $B$-band galaxy counts. The detection criterion is still three connected pixels with counts $3\sigma$ higher than the noise. This criterion transfers to the surface brightness as 22.86 mag $arcsec^{-2}$ for the images taken with the 24 inch and 24.21 mag $arcsec^{-2}$ for the images taken with the 88 inch. Our Monte Carlo simulation indicates that the completeness is at 20.5 mag for the images taken with the 24 inch and at 22.2 for the images taken with the 88 inch. The morphological index $r_4$ is calculated on the $I$-band image. For those galaxies with $B$ magnitude deeper than 20, their $K$-band magnitudes are generally beyond the limit of our detection. Hence, the star-galaxy classification cannot be conducted on the color-color diagram, and the morphological analysis is the only way to discriminate between stars and galaxies. However, for those galaxies fainter than $B = 21$ mag, their $r_4$ becomes noisy, so we measure the $B$-band galaxy counts only to $B = 21$ mag.

2.4. Star-Galaxy Classification

Star-galaxy classification was carried out in two ways: using object morphology and color properties. The $r_4$ as a morphological indicator is very sensitive to the shape of an object. Stars all have the same $r_4$, since they all have the same PSF. The $r_4$ of an extended object, however, must be larger than that of a PSF, since an extended object contributes more light at large radius than does a PSF. However, it has one disadvantage for morphological identification. As mentioned before, $r_4$ has to be calculated over a high S/N area, so compact galaxies can be misidentified as stars. A different classifying method must then be applied. The color-color diagram has been proved as a good method to discriminate between stars and galaxies (Gardner 1992), since on an $I - K$ versus $B - I$ color-color diagram, stars are clearly separated from galaxies. As Gardner (1992) noted, the separation line is $(B - I) - 2.5(I - K) = -2.0$. We found that this line separates our data well; see Figure 2. With these two methods, our final criteria to identify a galaxy are that an object has $r_4 \geq (r_4)$_det or that an object has $(B - I) - 2.5(I - K) > -2$ Figure 2 shows that both methods are consistent with each other, as almost all morphologically identified galaxies also lie below the separation line in the color-color diagram.

3. K-BAND GALAXY NUMBER COUNTS

3.1. Number Counts

The $K$-band galaxy number counts are shown in Figure 3. Due to the different completeness limits in different fields, the counts on each field were corrected separately, as described in § 2.3. The final counts are the average of all fields weighted by their areas. The number counts cover the magnitude range from $K = 12$ to $K = 16$. The fitted logarithmic slope of our observed counts shown as filled circles on the plot, is $d \log N/dm = 0.689 \pm 0.013$ (the Euclidean value is 0.6). The data are also presented in Table 2. The 1$\sigma$ errors for the counts in each bin are also shown, and a detailed discussion is given in § 3.2. The average field-to-field variation among our six fields at each magnitude bin is also listed in Table 2. We found that this variation has a minimum at $K = 14.5$ of only 5%. At the bright end, the variation results from the Poisson noise. However, at the faint end this variation may be caused by other factors, as discussed in the following text.

In Figure 3, we also show the data from other surveys. In general the agreement between the surveys is excellent. Our
counts at $K = 11.75, 12.25$ match well the counts of Mobasher et al. (1986). Between $K = 12.5$ and $K = 15$ our counts are slightly higher than the other counts. In this magnitude range, however, both the Hawaii medium-deep survey (HMWS) (Gardner 1992) and the Glazebrook et al. (1994) survey have much larger error bars. We note also that between $K = 15$ and $K = 16$ our counts are systematically higher than those of the HMWS. Though the difference is only about 10%, within the 1σ error bars of the HMWS, this may also be due to the difference between the two photometric systems used. We note also that over the same magnitude range, the counts of Jenkins & Reid (1991), HMDS, and HDS (Gardner 1992) are all slightly higher than the present data, probably due to their large Poisson noise. Recently, Gardner et al. (1996) have also completed a wide-field $K$-band survey. Their coverage is nearly 10 deg$^2$, about the same size as ours. Their counts in the range $13 < K < 16$ are within 1σ of our counts. However, their counts at the bright end of $K < 12.5$ are higher than ours. We argue that this difference is very likely due to the small sample statistics. The comparison between the observed counts and model predictions will be given in § 3.4.

3.2. Uncertainty in the Number Counts

Three factors contribute to the uncertainty in the galaxy number counts: the Poisson noise, the galaxy distribution, and the magnitude error. Understanding such uncertainties is the key to modeling the galaxy number counts, especially in obtaining the normalization factor $\phi_\ast$. We analyze first the uncertainty of the galaxy number counts caused by the Poisson noise and the galaxy distribution. Several authors (Glazebrook et al. 1994; Djorgovski et al. 1995) have noted the contribution of galaxy clustering to the uncertainty. However, the distribution of large-scale structures such as rich clusters and large voids are poorly known. We can model only the uncertainty caused by the galaxy-galaxy correlation, which is well known.

We give first the solution of the error caused by galaxy-galaxy correlation. We approach this problem in nonrelativistic form. Since the galaxy correlation scale is about 5 h$^{-1}$ Mpc, the nonrelativistic approach gives a good approximation. Here 5 Mpc corresponds to an angular size of 0.8° at a redshift of 0.15, a characteristic redshift of this $K$-selected galaxy sample. The uncertainty for a galaxy sample (Peelers 1975; Roche et al. 1993; Ferguson & Binggeli 1994) in one field can be written as

$$\sigma_i^2 = N_i + 2.24N_i^2 \Omega_i^{1 - \gamma/2},$$

where $i$ means the $i$th field, $\Omega_i$ is its area in units of square degrees, $A$ is the constant in an angular correlation function (Peelers 1980), viz.,

$$A = r_0^2 \Gamma(\gamma/2) \int_0^{\infty} x^{\gamma - 2} p^2(x)dx \Gamma(\gamma/2) \int_0^{\infty} x^2 p(x)dx,$$

$p(r)$ is a selection function, $r_0 = 5$ h$^{-1}$ Mpc, and $\gamma = 1.77$. For a sample with apparent magnitude $m$,

$$p(r, m) = \phi(m - 5 \log r - 25),$$

where $\phi(M)$ is the luminosity function. We adopt the Mobasher et al. (1993) $K$-band luminosity function with $M_K = -23.59 + 5 \log h$ and $\alpha = -1$. For the observed galaxy number counts, each bin is a sample with apparent magnitude $m$. Therefore, by applying equation (4) to equation (3) to calculate the constant $A$, then putting equation (3) into equation (2), we obtain an analytical solution of the uncertainty in observed galaxy counts at each magnitude,

$$\sigma_i^2 = N_i(m) + 5.3 \left( \frac{r_0}{r_X} \right)^\gamma \Omega_i^{1 - \gamma/2} N_i^2(m),$$

and $5 \log r_0 = m - M_\ast - 25$, where $N(m)$ is the number of observed counts in each bin. The final uncertainty for the number of counts per magnitude per square degree in all fields is

$$\sigma(m) = \frac{\sqrt{\sum \sigma_i^2}}{\Omega \Delta m},$$

where $\Omega \Delta m$ is the bin size and $\Omega$ is the total area $[\Omega_K(K < 14.5) = 9.81 \text{deg}^{-2}$ and $\Omega_K(K > 14.5) = 8.23 \text{deg}^{-2}]$. Figure 4 shows the contribution of both Poisson noise and galaxy correlation uncertainty to the total error in this survey. The 1σ errors of the observed counts calculated by

\begin{table}[h]
\centering
\caption{K-Band Galaxy Counts}
\begin{tabular}{cccc}
\hline $K$ & $N$ & $\sigma$ & $\sigma/(\%)$\\
\hline 11.25 & 0.2 & 0.2 & \ldots \\
11.75 & 1.0 & 0.5 & \ldots \\
12.25 & 2.5 & 0.7 & 68 \\
12.75 & 7.1 & 1.3 & 36 \\
13.25 & 14.5 & 1.9 & 41 \\
13.75 & 30.0 & 2.7 & 18 \\
14.25 & 65.4 & 4.2 & 10 \\
14.50 & 99.2 & 7.6 & 5 \\
14.75 & 157.5 & 9.8 & 7 \\
15.00 & 224.1 & 11.8 & 13 \\
15.25 & 321.4 & 14.3 & 11 \\
15.50 & 495.9 & 18.5 & 21 \\
15.75 & 634.9 & 21.1 & 10 \\
16.00 & 825.1 & 24.3 & 15 \\
\hline
\end{tabular}
\end{table}
using the above equations are listed in the third column of Table 2. It can be proved that for a survey with small sky coverage, the uncertainty caused by galaxy correlation is much smaller than the Poisson noise. As we can see in Table 2, the $1 \sigma$ is less than the field-to-field variation at $K > 15$ but comparable to the field-to-field variation at $K < 15$. Hence, it is very likely that other factors (rich clusters and large voids) than the Poisson noise contribute mainly to the field-to-field variation at the deep magnitude ($K > 15$) counts.

Magnitude errors may also cause changes of the galaxy number counts. These magnitude error result from two sources: systematic error and random error. In our case, the systematic error is the error in the zero point for the photometry, which in $K$-band was $\sigma_s \sim 0.05$ mag between observing runs. This error does not change the slope of $\log N$, but it shifts the $\log N$ in the horizontal direction in the count-magnitude diagram. We can transfer this magnitude error to the count error as

$$\frac{\sigma}{N(m)} = \alpha \sigma_s,$$

where $\alpha$ is the slope of $\log [N(m)]$. If we take the slope of 0.689 and $\sigma_s$ of 0.05, we obtain $\sigma/N = 3.5\%$, which is less than the field-to-field variation. The final contribution of this systematic error to the galaxy counts will be less than 3.5%, since the final result is the average counts of all observing runs.

Random error in the magnitudes can also change $\log N$. In the $K$-band survey, the sky background counts are much higher than galaxy counts. Hence, the random error in the magnitude of a galaxy is mainly caused by the sky background noise. Our Monte Carlo simulation indicates that the random error changes increasingly from 0.01 mag at $K = 13$ mag to 0.2 mag at $K = 16$ mag. The observed profile of the counts as a function of magnitude is a result of the real profile of the counts convolving with the random error distribution function, which is usually a Gaussian distribution. If the random error $\sigma_r$ is a constant, we can obtain an analytical solution as

$$\log (N)_{\text{obs}} = \log (N)_{\text{real}} + 1.15 \sigma_r^2 .$$

However, we have known that the $\sigma_r$ increases when the $K$ magnitude becomes faint. Though we cannot work out an analytical solution in this case, we can analyze this problem qualitatively. As both random magnitude error and intrinsic galaxy counts increase with increasing magnitude, on average there are more faint galaxies appearing erroneously in a brighter bin than brighter galaxies appearing erroneously in a fainter bin. Hence, the observed slope of $\log (N)$ becomes steeper than the real one. This trend can be seen also in the above equation. As we consider the slope change in the magnitude range from $K = 13$ to $K = 16$, this range is much larger than the random magnitude error $\sigma_r = 0.2$. By considering that only the galaxies at nearby bins can contribute to increasing of the galaxy counts erroneously, we argue that it is a good approximation to use the above equation to estimate the change of the slope as

$$\Delta \alpha = 1.15 \sigma_r^2 \frac{\sigma_{12}^2 - \sigma_{22}^2}{m_1 - m_2} .$$

As a first-order approximation, we use $\alpha = 0.689$, $\sigma_{12} = 0.2$ at $m_1 = 16$ and $\sigma_{22} = 0.01$ at $m_2 = 13$ to obtain that $\Delta \alpha = 0.008$ and $\Delta N/N = 5.1\%$ at $K = 16$. Since the $1 \sigma$ error of the slope from fitting is 0.013, this effect does not change the slope of the counts significantly.

4. B-band galaxy number counts

The $B$-band galaxy counts are presented in Figure 5, together with the data from other surveys. The data are also listed in Table 3. The purpose of measuring the $B$-band counts is to monitor our fields. Though we selected the fields carefully, we still need to know if there are any special galaxy distribution structures in our fields to distort the galaxy counts. The $B$-band galaxy counts have been studied substantially, as summarized by Koo & Kron (1992). In the $B$-band magnitude range (14–21 mag) that our counts cover, some survey areas cover as much as 4300 deg$^{-2}$ (Maddox et al. 1990). Our $B$-band galaxy counts are consistent with the counts of other $B$-band surveys, including the Maddox et al. survey. This consistency means that our fields are an average field, and the $K$-band galaxy counts measured from our fields may not be distorted. The physical...
the relation between the $K$-band counts and the $B$-band counts will be discussed later.

The 1σ error of the $B$-band counts listed in Table 3 are calculated by using equations (5) and (6) with a set of parameters of a $B$-band luminosity function. Like the $K$-band counts, this error is also dominated by the Poisson error. The field-to-field variations for the $B$-band counts are listed in the third column of Table 3. Our zero-point error for the $B$-band photometry is about 0.03 mag, and the slope of the $B$-band counts in the range of 15–21 mag is 0.38. We estimate that the error of the counts caused by this systematic error is at about the 1% level. The random error of the $B$ magnitude is different from that of the $K$ magnitude. Since the $B$-band sky background is very low, the random error is caused mainly by the photo counting statistics of a galaxy and is inversely proportional to square root of its counts. Hence, the faint galaxies have larger magnitude errors than the bright galaxies. The random error is only about 0.01 at $B = 21$ mag, and negligible at $B = 16$ mag. Putting this error and the slope of the $B$-band counts in equation (9), we find that the steepening effect of the random magnitude is negligible for the $B$-band counts.

5. MODELING THE $K$-BAND COUNTS

5.1. No-Evolution Model

The $K$-correction is also a key issue in understanding a faint galaxy's magnitude. In the optical bands, the $K$-correction is a strong function of morphological type (Cowie et al. 1994). Thus, in fitting no-evolution models to optical counts, usually measured in the $B$ band (King & Ellis 1985; Yoshii & Takahara 1988), the mix of morphological type has to be determined. We also have to obtain the type-dependent luminosity functions, which are usually assumed to be the same as for the observed total luminosity function. The no-evolution modeling for the optical counts is, therefore, highly dependent on the mix of morphological types. However, the $K$-correction in the $K$ band is different. First, the near-infrared spectrum of a galaxy is flatter and more featureless than in optical band, so the $K$-band-corrected magnitudes are consequently more reliable than the optical corrected magnitudes. Second, the $K$-correction in the $K$ band is only a weak function of morphological type. Up to $z = 1$, to a good approximation, we can ignore the differences of $K$-correction in the $K$ band among different Hubble types (Glazebrook et al. 1994). The details of the $K$-band $K$-correction, however, are poorly determined. Currently the $K$-band $K$-correction is derived either from evolving galaxy models (Rocca-Volmerange & Guideroni 1988; Bruzual & Charlot 1993; Buzzoni 1995) summarized by Glazebrook et al. (1995a), or from interpolation of the $J-K$ and $H-K$ colors (Cowie et al. 1994). The $K$-corrections derived from these methods, as we see in Figure 6, do not agree with each other exactly. Considering the uncertainties of these methods, however, the differences are reasonable. As seen in Songaila et al. (1994), even at their deepest magnitude ($K = 20$) the median redshift of the $K$-selected galaxies is still substantially less than 1. Since our number counts are below $K = 16$, we can construct a no-evolution model for our $K$-band counts with a general $K$-band luminosity function and a simple $K$-correction term.

The traditional $K$-band luminosity function (Yoshii & Takahara 1988) is derived in this way: first by assuming that each Hubble type has a uniform color, $B-K$; then by converting each optical type-dependent luminosity function into $K$-band type-dependent luminosity function according to color; and finally by adding all type-dependent luminosity functions weighted according to the type mix. More directly, we can use just the observed $K$-band luminosity function. Unfortunately, the $K$-band luminosity functions reported in the literature do not agree with each other well. Mobasher et al. (1993) conducted a redshift survey on a $K$-selected subsample from the $B$-selected sample of the Anglo-Australia Redshift Survey and constructed the first $K$-band luminosity function fit to a Schechter function with $M_{*} = -23.59 (h = 1$ hereafter) and $\alpha = -1$. The $K$-band luminosity function that Glazebrook et al. (1995a) obtained directly from their $K$-band survey has a similar shape, but their $M_{*}$ is significantly fainter, $M_{*} = -22.75$. The most recent determination of Cowie, Songaila, & Hu (1996) finds an $M_{*}$ consistent with that of Mobasher et al. (1993) and a similar shape. Both luminosity functions will be used in constructing the no-evolution model.

The no-evolution model can also be presented in another way, as a mean color-magnitude relation. Specifically, we

| $B$  | $N^a$ | $\sigma^b$ | $\sigma_0(\%)^c$ |
|------|------:|---------:|----------------:|
| 15.0 | 0.5  | 0.2     | 20              |
| 15.5 | 0.8  | 0.4     | 32              |
| 16.0 | 2.3  | 0.8     | 11              |
| 16.5 | 3.3  | 0.8     | 7               |
| 17.0 | 9.5  | 1.6     | 19              |
| 17.5 | 13.6 | 1.9     | 13              |
| 18.0 | 26.2 | 2.6     | 6               |
| 18.5 | 49.9 | 3.6     | 8               |
| 19.0 | 83.6 | 5.6     | 7               |
| 19.5 | 171.5| 8.0     | 8               |
| 20.0 | 315.4| 13.5    | 7               |
| 20.5 | 596.0| 18.7    | 7               |
| 21.0 | 931.1| 23.3    | 5               |

* $N$ is in units of mag$^{-1}$ deg$^{-2}$.

* $\sigma$ is calculated by using eqs. (5) and (6).

* $\sigma_0$ is the ratio of the field-to-field variation to the number counts.

![Fig. 6](image-url)
will derive \( \langle I - K \rangle \) as a function of \( K \) magnitude. Due to the difference of the \( I \)-band \( K \)-correction for different spectral type galaxies, the \( \langle I - K \rangle \) of each type of galaxy has to be treated separately. Since we do not have the \( K \)-band type-dependent luminosity function we have to adopt the general \( K \)-band luminosity function for each type galaxy. To be consistent with the \( I \)-band \( K \)-correction in Cowie et al.'s paper (1994), we simply divide galaxies into E/S0, spiral, irregular galaxies, and adopt the \( I \)-band \( K \)-correction directly from their paper. Then, for each classified type galaxies, we have

\[
\langle I - K \rangle = \langle I - K \rangle_{z=0} + \frac{\int n(z, m)(kc(z) - kc(z)dz}{\int n(z, m)dz},
\]

where \( n(z, m) \) is the no-evolution model of the galaxy counts as a function of redshift and magnitude, and \( kc \) and \( kc \) are the \( I \)- and \( K \)-band \( K \)-correction terms. In Figure 7, the models of \( \langle I - K \rangle \) for E/S0, spiral, and irregular galaxies are plotted in comparison to the observed data. Each model has been normalized to the colors of the bright galaxies whose morphologies in their CCD images are classified by authors. The models with faint \( M_* \) predict bluer colors at the faint magnitude end than those with bright \( M_* \). This is because, for a flux-limitted sample, a model with faint \( M_* \) predicts fewer distant galaxies than a model with bright \( M_* \), and the \( I \)-band \( K \)-correction makes the color of distant galaxies redder than those of nearby galaxies. The observed \( \langle I - K \rangle \) lies between the models of E/S0 and spiral galaxies with the same trend as those of the models. This indicates that the galaxies in the \( K \)-selected sample are mainly E/S0 and early-type spiral galaxies, and a no-evolution model is good enough to fit the observed color. To combine our models to fit the observed data suggests that, in the \( K \)-selected galaxy sample, about 50% of them are E/S0, another 50% are spiral galaxies, and there are very few irregular galaxies.

5.2. Local \( K \)-selected Galaxies

Understanding the local galaxy sample is also essential in connecting the model to the observed counts, since the local galaxy sample serves as a reference point for the models. We selected a subsample with a limiting apparent magnitude of \( K = 15 \) mag. If we also add the counts of Mobasher et al. (1986), the local counts cover from \( K = 10 \) to \( K = 15 \). For such a magnitude range, a no-evolution model can be characterized by its slope. We have calculated the slopes of no-evolution models with different luminosity functions, different geometries, and different \( K \)-corrections. The slope of a no-evolution model in \( 10 < K < 15 \) is independent of \( q_0 \) and varies only from 0.605 to 0.623, for all current varieties of \( M_* \) and the \( K \)-correction. The result is summarized in Table 4. We conclude that the slope is very weakly dependent on the \( M_* \), and the difference in the current \( K \)-corrections does not change significantly the no-evolution model. The slope of the observed counts at this magnitude range, however, is much larger than the maximum slope of the theoretical prediction. As shown in Figure 8, the slope of the counts in this survey is 0.69 ± 0.014. When we combine our counts with those of Mobasher et al. (1986), the slope becomes 0.68 ± 0.012. Gardner et al. (1996) obtained a flatter slope, as 0.63 in \( 10 < K < 15 \). However, by excluding their bright counts measured with only a few galaxies, their slope in \( 13 < K < 15 \) is 0.65, which is not as steep as ours. It is possible that their fields contain more bright galaxies than the average, since their \( B \)-band counts below \( B = 18 \) are significantly higher than the \( B \)-band counts of Maddox et al. (1990). By combining our counts with those of Gardner et al. (1996), we still obtain a much steeper slope of 0.67 in \( 13 < K < 15 \). Hence, the no-evolution model slopes are 5–7 \( \sigma \) away from the observed slope. Normalizing our

![Fig. 7.—Left: Plot of \( I - K \) vs. \( K \). Right: The models of \( \langle I - K \rangle \) are plotted with the observed data. The upper lines are the models of E/S0 galaxies; the middle lines are the models of spiral galaxies; and the lower lines are the models of irregular galaxies. The solid lines are the models with the luminosity function of Mobasher et al. (1993), and the dashed lines are the models with the luminosity function of Glazebrook et al. (1995a). The difference between these two models is discussed in the text.](image1)

![Fig. 8.—The \( K \)-band galaxy counts are fitted by a pure no-evolution model (solid line) and a no-evolution model with a density gradient (dashed line). It is clear that the slope of a pure no-evolution model is very different from that of the observed counts. The crosses are the counts of Mobasher et al. (1986); the filled circles are the counts of this survey; and the triangles are the counts of Gardner et al. (1996). Our fitting does not include the counts of Gardner et al. (1996). However, their counts match our model very well in \( 13 < K < 15 \).](image2)
no-evolution model with the steepest slope to the counts at $K = 10.25$ as in Figure 8, we find that the model cannot fit the observed counts. The result is independent of our selection of luminosity functions, normalizations, and geometries. The only parameter that determines the slopes of no-evolution models is the $K$-correction. Though the $K$-corrections derived from various methods are quite consistent with each other, as we indicated above, they could still be poorly determined. Near-infrared emission features could be missed in the stellar synthesis models and the color interpolation. The features in between $2.0 \mu m$ to $2.2 \mu m$, such as He i, H$_2$ S(1), and Br$_\gamma$, could change the $K$-correction at low redshifts and therefore change the slope of a no-evolution model in $10 < K < 15$. We found that we could fit the number counts by increasing artificially the $K$-correction by a factor of 3 between $z = 0$ and 0.2. However, we argue that such a large correction (more than a magnitude) is very unlikely to be the case. Ridgway, Wynn-Williams, & Becklin (1994) took near-infrared spectroscopy on their infrared-luminous galaxy sample. Most of the galaxy spectra in the range of $2.0 \mu m$ to $2.2 \mu m$ are featureless, even where the infrared-luminous galaxies are gas-rich galaxies. Our K-selected sample is dominated by early-type galaxies and cannot have such strong emission features. Hence, we do not think that the current $K$-corrections can deviate from the real one by such a large factor. The difference between the observed counts and the model prediction at $13 < K < 15$ implies either galaxy evolution at low redshifts or a local deficiency of galaxies.

Galaxies with apparent magnitudes of $13 < K < 15$ are located at $z < 0.2$ (Songaila et al. 1994). Galaxy evolution at such low redshifts was proposed first based on the $B$-band counts (Maddox et al. 1990). Maddox et al. found that there was an excess in their $B$-band counts at $18 < B < 20$ over a no-evolution model. Their magnitude range in the $B$-band is equivalent to $13 < K < 15$ in the $K$-band. Such galaxy evolution, however, is very unlikely to be luminosity evolution, since many redshift surveys (Condon 1989; Ellis et al. 1996; Glazebrook et al. 1995b; Songaila et al. 1994) in both $B$-band and $K$-band have shown that galaxies with luminosities brighter than $L_\ast$ ceased evolving long before $z = 0.5$. The galaxy evolution at low redshifts suggested by some of these authors occurs only among low-luminosity galaxies. By analyzing $K$-band and $B$-band luminosity functions at different $z$ (Cowie et al. 1996; Ellis et al. 1996) they found that there were more dwarf galaxies in the past than now. Cowie et al. (1996) suggest further that higher density of dwarf galaxies in the past is due to the evolution of the formation process. However, this evolution is not significant at $z < 0.2$. We will be able to confirm this argument only after we compare the luminosity functions at $z = 0$ and at $z = 0.2$, constructed from this sample in the follow-up redshift survey.

A local deficiency of galaxies seems the best explanation of the steep counts at the bright end. This possible explanation has been proposed based upon the $B$-band counts (Shanks 1989; Driver, Windhorst, & Griffiths 1995) and radio source counts (Windhorst, Mathis, & Neuschaefer 1990; Condon 1989). The model requires that the Galaxy happens to be in an extremely large low-density region in the universe with a scale from $300 h^{-1}$ Mpc to $600 h^{-1}$ Mpc (corresponding to $z \sim 0.1$--0.2). The galaxy number density of our neighborhood is then lower than the galaxy number density at $z \sim 0.1$--0.2 which may be the true average galaxy number density of the universe. The difference between the observed counts and the no-evolution model at $13 < K < 15$ normalized at $K = 10.25$ then represents the difference between the density of our neighborhood and the average density of the universe. We find that the following function of $\phi_\ast(z)$ can increase the slope of a no-evolution model at $K < 15$ to 0.69 (see Fig. 8):

$$\phi_\ast(z) = \phi_\ast[1 + \exp \left(-z/(0.1)^2\right)]^{-1}. \quad (11)$$

This function is almost constant at $z > 0.2$, and so it does not change significantly a no-evolution model at $K > 16$. This density profile is very arbitrary, since the observed galaxy counts provide little constraint. However, this function should also fit the $B$-band bright counts if there is a real local deficiency. From the $B$-band bright galaxy surveys (Shanks 1989; Maddox et al. 1990), we know already that the slope of the $B$-band bright counts below $B = 20$ is steeper than that of a no-evolution model. Figure 5 shows the observed $B$-band counts (including ours) and the no-evolution model made by Ellis (1987). Furthermore, our local hole model predicts that the galaxy density at $z = 0.2$ is twice the local galaxy density at $z = 0$. When Shanks (1989) normalized his $B$-band no-evolution model at $B = 18$, the model indeed overpredicted the local galaxy density by a factor of 2. Maddox et al. (1990) also found that their $B$-band counts at $B = 20$ had an excess over the no-evolution model by a factor of 2. As many redshift surveys indicate, galaxies with $B \sim 18$--20 are located at about $z = 0.2$. Thus, the $B$-band counts show a similar density profile to that of the $K$-band counts. This indicates a consistency for the local deficiency model. However, since we also do not know exactly where galaxies stop evolving, a redshift survey on a very large bright sample, such as this large $K$-selected sample, is required to distinguish these two effects on the steep counts at the bright end. Such a redshift survey will be large enough to provide precise luminosity functions at different redshifts. If the shape of the $K$-band luminosity functions in this redshift range remains the same, but $\phi_\ast$ changes with $z$, this will confirm that the large-scale structure produces the steep slope at the bright end of the observed counts.

Voids and superclusters are the largest structures ever found in the universe (Rood 1988; Bahcall 1988). Their scales are usually from $20 h^{-1}$ Mpc to $120 h^{-1}$ Mpc. Since the previous large redshift surveys have limited depth, no structure with a scale larger than $200 h^{-1}$ Mpc has been discovered yet. The presence of a local low-density region with a scale larger than $300 h^{-1}$ Mpc must have a fundamental effect in our measurement of $H_0$ and $\Omega$ (Turner, Cen, & Ostriker 1992). It implies that local measurements on smaller scales may overestimate the "true" value of $H_0$ by as much as 33% and underestimate $\Omega$ by a factor of 2. If true, this would go far to resolve current timescale problems at the expense of introducing extraordinarily large-scale inhomogeneity into the cosmological model.

6. CONCLUSION

We have completed a $K$-band field galaxy survey with a total coverage of about 10 deg$^2$. The results are summarized below.

1. The $K$-band counts from this survey extend from $K = 12$ to $K = 16$. They are well matched to the counts of other surveys in this range but have much smaller error bars.
than previous studies.

2. For a pencil-beam survey, the error caused by galaxy-galaxy correlation is smaller than the Poisson noise. At the faint end of our counts, the error is dominated by the large-scale structures.

3. We construct no-evolution models for the K-band counts by using a variety of luminosity functions, geometries, and K-corrections. In the range of $10 < K < 15$, these models yield very similar predictions.

4. The shape of the bright-end counts does not fit no-evolution models. We find that none of the theoretical and observational uncertainties that we have been able to identify can cover this discrepancy. We, then, conclude that there are changes in the galaxy luminosity function at low redshifts for a K-selected sample. The steep slope may be due to a change in $\phi_*$ with redshift, which reflects a substantial local deficiency of galaxies over scale sizes of $300 h^{-1}$ Mpc. This would imply that the universe is inhomogeneous on extremely large scales and that local measurements overestimate $H_0$ by factors of up to 33% and underestimate $\Omega_0$ by a factor of roughly 2. The conclusion needs to be confirmed by the follow-up redshift survey.

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