THE HAWAII+ANGLO-AUSTRALIAN OBSERVATORY K-BAND GALAXY REDSHIFT SURVEY. I. THE LOCAL K-BAND LUMINOSITY FUNCTION

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ABSTRACT

We present the K-band local luminosity function derived from a sample of 1056 bright (K < 15) K-selected galaxies from the Hawaii+Anglo-Australian Observatory (AAO) K-band redshift survey. The Hawaii+AAO K-band redshift survey covers four equatorial fields with a total area of 8.22 deg². We derive both the nonparametric and Schechter luminosity function from our data and determine \( M^*(K) = -23.70 \pm 0.08 + 5 \log_{10}(h) \), \( \alpha = -1.37 \pm 0.10 \), and \( \phi^* = 0.013 \pm 0.003 \) h³ Mpc⁻³ for a universe with \( \Omega_m = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \). We also measure the K-band luminosity function for the early- and later type galaxies from our morphologically classified subsample. It appears that later type galaxies have a fainter \( M^* \) and a steep slope, while early-type galaxies have a much brighter \( M^* \) and a quite flat slope in their K-band luminosity functions. This is consistent with what has been found in optical-type dependent luminosity function. The K-band luminosity density derived using our luminosity function is now measured at a similar redshift depth to optical luminosity densities in the Sloan Digital Sky Survey redshift survey. It is 2 times higher than the previous measurement from the shallower 2MASS sample and resolves the previously reported discrepancies between optical and near-infrared luminosity densities.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: luminosity function, mass function — infrared: galaxies — surveys

1. INTRODUCTION

The galaxy luminosity function is an important quantity in the study of galaxy evolution and formation. Traditionally, galaxy luminosity functions have been derived in optical bands. It is now clear that extragalactic studies in optical bands suffer several systematic uncertainties and complexities compared to those using near infrared bands. In particular, dust extinction has little effect on K-band magnitudes: the K-correction in the K-band is a much smaller and better understood quantity than in the optical bands, and it is independent of galaxy spectral types for \( z < 1 \). Because of this, it is easier to detect a high-redshift elliptical galaxy in an infrared band than in optical bands. A galaxy’s near-infrared luminosity is also a good tracer of its stellar mass independent of spectral type (Cole et al. 2001; K. Glazebrook et al. 2003, in preparation). Recent theoretical studies show that the K-band galaxy luminosity function is a powerful constraint on galaxy formation theory (Baugh et al. 1998; Kauffmann & Charlot 1998).

Most near-infrared surveys, however, have been modest in size due to the small size of available infrared detectors. The advent of large-format infrared array detectors has made possible a variety of wide-field near-infrared surveys, ranging from several at the 10 deg² level (Gardner et al. 1996; Huang et al. 1997) up to the largest of them all, the 2 Micron All-Sky Survey (2MASS; Skrutskie et al. 1997). Obtaining optical redshifts for a K-selected sample, however, is difficult because the wide range in optical–infrared colors results in the requirement for a wide range of exposure times to acquire optical spectroscopy. In particular, very long exposures are required to secure redshifts for the reddest objects. Because of this, there are only a few K-band luminosity functions available. The early K-band luminosity functions were derived from small size samples with the number of galaxies ranging from 100 to 500 (Mobasher et al. 1993; Glazebrook et al. 1995; Gardner et al. 1997; Szokoly et al. 1998; Loveday 2000). After the second incremental release of 2MASS data, two teams (Cole et al. 2001; Kochanek et al. 2001) used the overlap between the 2MASS Extended Source Catalog and two existing optical redshift databases, CfA2 (De Lapparent et al. 1988) and 2dFGRS,7 to obtain very large (>4000), if very shallow (\( K < 13 \)), K-selected redshift samples to derive the local K-band luminosity function. However, the mean redshift for these samples is 0.025 for the CfA sample (Kochanek et al. 2001) and 0.05 for the 2dF sample (Cole et al. 2001).

The observational goal of the Hawaii+Anglo-Australian Observatory (AAO) K-band redshift survey was to obtain a large medium–deep K-selected galaxy sample with redshifts and optical–infrared colors. Both optical (B and J) and near-infrared (K) images were taken at Mauna Kea Observatory with total infrared coverage of totaling 8.22 deg² (Huang et al. 1997). The spectroscopic observations were carried out on the Anglo-Australian Telescope (AAT) with the two degree field facility (2dF). In this paper, we report K-band luminosity functions derived from a subsample of 1056 bright (\( K < 15 \)) galaxies. The median redshift of this sample is 0.138 with the redshift distribution tail extending to \( z = 0.5 \). In this paper, we adopt the \( \Omega_m = 0.3 \), \( \Omega_{\Lambda} = 0.7 \), and \( H = 100 \) km s⁻¹ Mpc⁻¹ cosmology model.

A comparison of the K-band luminosity functions derived

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using different cosmology models is also presented. We briefly summarize the observation and data reduction in § 2. In § 3, we present the $K$-band luminosity functions. In § 4, we compare our luminosity function with others and discuss the difference. We summarize our results in § 5.

2. OBSERVATIONS

Huang et al. (1997) have described in detail the acquisition and processing of our $B$, $I$, and $K$-band imaging. In brief, the imaging survey was carried out at Mauna Kea Observatory and represents over 70 nights of time on the University of Hawaii 88 and 24 inch telescopes. The survey consists of four equatorial fields covering a total area of 8.22 deg$^2$. The optical and near-infrared limiting magnitudes are $B_{\text{limit}} = 22$, $I_{\text{limit}} = 20.5$, and $K_{\text{limit}} = 16.0$. The spectroscopic observations for the $K$-selected sample were carried out at the AAT with 2dF, a multibin spectrograph that can observe 400 targets within a 2$^\circ$ field of view. These observations took approximately 10 clear nights spread out over the period 1997–1999. The exposure time for a spectroscopic observation was determined by the $I$ magnitude of each object; for objects with $I < 18.5$ ($I-K < 2.5$ the $K = 16$ limit), 1 hr exposure times sufficed. For the redder objects ($18.5 < I < 21$), exposure times of up to 4 hr were used. Weather variations meant that some 2dF observations were not as deep as others. When a redshift was not secured at a first attempt, the object was flagged for reobservation in a later 2dF configuration. Multiple 2dF configurations were observed on each field to ensure maximal completeness.

Our $K < 15$ sample is highly complete in redshift. From a total of 1201 objects imaged with $K < 15$, redshifts were obtained for 1056 galaxies. A further 59 objects turned out to be stars, leaving only 86 objects without identification. These objects are assumed to be galaxies for the purposes of incompleteness correction. Figure 1 shows the redshift distribution of the sample. The median redshift for the $K \leq 15$ sample is 0.136. We calculate absolute magnitudes with a $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$ cosmology and use recently published $K$-correction due to Mannucci et al. (2001). $K$-corrections also have been tested using spectral evolution models that best fit the observed colors (Fioc & Rocca-Volmerange 1997). No significant difference was found in either the $K$-corrections or the resulting luminosity functions.

3. THE LUMINOSITY FUNCTION

We use the stepwise maximum likelihood (SWML; Efstathiou et al. 1988) to derive the nonparametric luminosity function and the STY method (Sandage, Tamman, & Yahil 1979) to fit the Schechter function to the data. After obtaining $M^*$ and $\alpha$ by fitting Schechter function to our data, we use the minimum variance estimator (Davis & Huchra 1982) to determine the $\phi^*$. Both STY and SWML methods are based on the maximum likelihood principle and are therefore valid only for a complete galaxy redshift sample. Correction for our sample’s (small) incompleteness is therefore needed. Zucca et al. (1994) and Lin et al. (1996, 1999) have shown that a weighted STY method can be used to derive a luminosity function from an incomplete sample. In the weighted STY method, if a galaxy in the sample has no redshift, similar galaxies with redshifts (i.e., similar magnitude, similar color, or both) receive increased weight in calculating the likelihood to represent the galaxy without a redshift,

$$P_i = \left( \frac{\psi(L_i)}{1 \int \psi(L) dL} \right)^{w_i}.$$

Here $P_i$ is the probability for galaxy $i$ at redshift $z_i$, $\psi(L)$ is the luminosity function, and $w_i$ is the weight for galaxy $i$. For a complete sample, $w_i = 1$; otherwise, $w_i \geq 1$.

In our case, only 7% of targets do not have redshifts, so such a correction does not make a large difference. We fit Schechter functions to the sample both with and without correction. We follow Lin et al. (1996, 1999) in estimating the weight function for each galaxy with redshift in the sample. We divide the sample into apparent magnitude and color $I-K$ bins, and the weight $w_i$ assigned to galaxy $i$ with redshift $z_i$ is the ratio of total number of galaxies over the total number of galaxies with redshifts in the bin where the galaxies $i$ is. Since the incompleteness of the four fields varies, we have to calculate $w_i$ for galaxies in each field separately. Table 1 summarizes the result of the STY fitting with three different cosmological models, and Figure 2 shows the nonparametric $K$-band luminosity function and the Schechter function in the $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$ universe.

As shown in Table 1, the parameters of the Schechter function depend on the adopted cosmological models. This is because the median redshift is 0.138 where the effect of the geometry for the adopted cosmology model appears in calculating distance and the change of $\alpha$ is due to the correlation between $M^*$ and $\alpha$. There is a slight difference between the luminosity functions derived with correction and without correction. The $M^*$ calculated with correction is slightly brighter than that calculated without correction. This is because most of the galaxies without redshifts are near the $K = 15$ limit and are either bright galaxies at relatively high redshifts compared to the rest of the sample or local lower
luminosity function for the early-type galaxies has a bright types with the best fitting Schechter functions. The Figure 3 shows the derive the luminosity function of early-type (E/S0) and later type mergers or irregular galaxies. Therefore, we are able to spirals, and only a few with peculiar morphologies are possi-
ble while allowing us to have enough galaxies to derive the
K sample are assigned more weight. The consequence is to cause M** to become somewhat brighter and the faint end slope slightly steeper after correction.

Using the higher spatial resolution I-band images, Huang et al. (1998) was able to make a morphological classification for the very bright galaxies (K ≤ 14). Among 225 galaxies with K ≤ 14 in the sample, Huang et al. (1998) classified 111 galaxies as E/S0. Most of the remaining 114 galaxies are spirals, and only a few with peculiar morphologies are possibly mergers or irregular galaxies. Therefore, we are able to derive the luminosity function of early-type (E/S0) and later type (spiral and irregular galaxies) for the K ≤ 14 sample. Figure 3 shows the K-band luminosity function for both types with the best fitting Schechter functions. The K-band luminosity function for the early-type galaxies has a bright M** of M** = −23.56 ± 0.26 and a flat slope α = −1.04 ±0.31, while that for the later type galaxies, it has a much fainter M** of M** = −23.28 ± 0.28 and a steeper slope of α = −1.42 ± 0.31.

4. DISCUSSION

Recently, several K-band luminosity functions were derived either directly from K-band surveys (Glazebrook et al. 1995; Gardner et al. 1997; Szokoly et al. 1998) or from optical samples with K-band images (Mobasher et al. 1993; Loveday 2000). These luminosity functions are roughly in agreement with each other, given that most samples are small in size and have large statistical uncertainty. To compare the K-band luminosity functions in different cosmology models, Cole et al. (2001) convert all existing K-band luminosity functions to those in the Ωm = 0.3 and ΩΛ = 0.7 cosmology model. Table 2 shows the parameters of Schechter function for all K-band luminosity functions, including those we adopted from Cole et al. (2001) and ours. We also list sample size and limiting magnitude for each survey.

By comparing the Schechter functions, our luminosity function has a brighter M** and a steeper slope: only those of Szokoly et al. (1998) are close to ours. The rest of the luminosity functions have a M** at least 0.3 mag fainter than ours and a flat slope (α ~ −1), including two 2MASS luminosity functions (Cole et al. 2001; Kochanek et al. 2001) and that of Gardner et al. (1997), who had a similar sample to ours. For more accurate comparison, we plot the luminosity functions against each other in Figure 4. Figure 4 shows that our luminosity function is higher and steeper than the 2MASS luminosity functions and that of Gardner et al. (1997). This is in agreement with the comparison in Schechter functions that the 2MASS luminosity functions have fainter M**, lower φ*, and flat α.

There are two different important aspects between our sample and the 2MASS sample (Cole et al. 2001; Kochanek et al. 2001): different ways of measuring total magnitudes for galaxies and different redshift ranges for both sample. Each of them could cause the difference in deriving luminosity function. If we assume that both photometric methods measure true total magnitudes for K-selected galaxies, the difference between both K-band luminosity functions implies a change of luminosity function at different redshift ranges. Since our sample covers a wider redshift range, we are able to derive the K-band luminosity function in the lower redshift bin. This will allow us to test whether or not we are able to reproduce the results from the 2MASS sample using our lower redshift bin sample. The limiting magnitude in both Cole et al. (2001) and Kochanek et al. (2001) samples are around K ~ 13, which is too bright for our sample to be statistically significant. However, we can adopt a redshift-limited subsample that approximates their redshift range: it will simply extend ~2 mag further down the luminosity function. Thus, we set the limiting redshift z < 0.1 to approximate the redshift range to those of the 2MASS sample while allowing us to have enough galaxies to derive the luminosity function. Figure 4 shows that our luminosity function for the subsample with z < 0.1 matches the luminosity functions of Cole et al. (2001) and Kochanek et al. (2001) very well. We also fit the Schechter function to our

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**Table 1: Result of STY Fitting**

| Cosmological Model | M** − 5 + log(h) | α | φ* | L** |
|-------------------|-----------------|---|----|-----|
| Ωm = 0.3, ΩΛ = 0.7 (uncorr) | −23.64 ± 0.08 | −1.30 ± 0.11 | 0.014 ± 0.001 | 4.05 ± 0.13 |
| Ωm = 0.3, ΩΛ = 0.7 (corr1) | −23.70 ± 0.08 | −1.38 ± 0.09 | 0.014 ± 0.001 | 4.79 ± 0.16 |
| Ωm = 0.3, ΩΛ = 0.0 (uncorr) | −23.51 ± 0.08 | −1.25 ± 0.09 | 0.017 ± 0.002 | 4.14 ± 0.44 |
| Ωm = 0.3, ΩΛ = 0.0 (corr1) | −23.57 ± 0.08 | −1.33 ± 0.09 | 0.017 ± 0.002 | 4.82 ± 0.04 |
| Ωm = 1.0, ΩΛ = 0.0 (uncorr) | −23.36 ± 0.08 | −1.16 ± 0.09 | 0.020 ± 0.002 | 3.88 ± 0.41 |
| Ωm = 1.0, ΩΛ = 0.0 (corr1) | −23.41 ± 0.08 | −1.25 ± 0.09 | 0.020 ± 0.002 | 4.44 ± 0.40 |

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![Figure 2](image-url)  
**Figure 2:** K-band luminosity function derived from our K ≤ 15 sample with the best-fit Schechter function. Lower right corner: 1σ contour.
subsample with \( z < 0.1 \) and obtain that \( M^* = -23.10 \pm 0.15, \alpha = -0.93 \pm 0.16, \) and \( \phi^* = 0.012 \pm 0.004 \) Mpc\(^{-3}\), consistent with those derived using the 2MASS samples. This implies that the normalization of the luminosity function is a function of redshift, even at lower redshifts, and explains the apparent discrepancy in published estimates without needing to invoke systematic errors in deriving total magnitudes in both samples.

The steep slope of our \( K \)-band luminosity function is actually consistent with those of optical luminosity functions obtained in several current wide-field optical surveys. Folkes et al. (1999) derived a \( B \)-band luminosity function with \( \alpha = -1.28 \pm 0.05 \) using a large redshift sample obtained in the 2df Galaxy Redshift Survey (2dFGRS). Blanton et al. (2001) and the Sloan Digital Sky Survey (SDSS) team obtained the optical luminosity functions in \( u^*, g^*, r^*, i^*, \) and \( z^* \) bands, and the \( \alpha \) for these luminosity functions in the five bands are \( -1.38, \) \(-1.26, \) \(-1.20, \) \(-1.25, \) and \(-1.24, \) respectively. Cole et al. (2001) used the average color to transfer the SDSS \( z^* \)-band luminosity function to a \( K \)-band luminosity function with \( M^* = -23.67, \phi^* = 0.0127, \) and \( \alpha = -1.24, \) which are very close to the parameters of our luminosity function. We would like to point out that the peak of the redshift distribution for the SDSS sample is about 0.1, much closer to ours than to those of the 2MASS sample (Cole et al. 2001; Kochanek et al. 2001). This implies that the normalization of the luminosity function is a function of redshift, even at lower redshifts, and explains the apparent discrepancy in published estimates without needing to invoke systematic errors in deriving total magnitudes in both samples.

![Fig. 3.—K-band luminosity functions for the early- and late-type galaxies, which are different from each other: the luminosity function of the later type galaxies has a much steeper slope end than that of the early-type galaxies. The luminosity function for the early-type galaxies has a bright \( M^* \).](image)

### TABLE 2

| Sample                  | \( M^* \)  | \( \alpha \) | \( \phi^* \) | \( l_* \) | \( N \) | \( m_{\text{lim}} \) |
|-------------------------|------------|--------------|------------|-----------|-------|------------------|
| Mobasher et al. 1993    | -23.37 ± 0.30 | -1.00 ± 0.3  | 1.12 ± 0.16 | 1.96 ± 0.62 | 95    | \ldots          |
| Glazebrook et al. 1995  | -23.14 ± 0.23 | -1.04 ± 0.3  | 2.22 ± 0.53 | 3.19 ± 1.07 | 98    | \( K \leq 17.3 \) |
| Gardner et al. 1997     | -23.30 ± 0.17 | -1.00 ± 0.24 | 1.44 ± 0.20 | 2.36 ± 0.48 | 532   | \( K \leq 15.0 \) |
| Szokoly et al. 1998     | -23.80 ± 0.30 | -1.30 ± 0.20 | 0.86 ± 0.29 | 2.90 ± 1.27 | 110   | \( K \leq 16.5 \) |
| Loveday 2000            | -23.58 ± 0.42 | -1.16 ± 0.19 | 1.20 ± 0.08 | 2.86 ± 0.94 | 345   | \( b_7 \leq 17.15 \) |
| Kochanek et al. 2001    | -23.43 ± 0.05 | -1.09 ± 0.06 | 1.16 ± 0.10 | 2.27 ± 0.21 | 3878  | \( K \leq 11.25 \) |
| Cole et al. 2001        | -23.36 ± 0.02 | -0.93 ± 0.04 | 1.16 ± 0.17 | 1.94 ± 0.29 | 5683  | \( K \leq 13.2 \) |
| This paper              | -23.70 ± 0.08 | -1.38 ± 0.09 | 1.30 ± 0.20 | 4.79 ± 0.16 | 1056  | \( K \leq 15.0 \) |
Before the 2MASS sample was available, there were no $K$-selected samples with morphological classification, hence no type-dependent $K$-band luminosity functions. Loveday (2000) derived $K$-band luminosity functions for the emission-line galaxies (ELGs) and also for the galaxies without emission lines (non-ELG). He found that the $M^*$ of the $K$-band luminosity function for ELG is 1 mag fainter than that for non-ELG. For the first time, Kochanek et al. (2001) was able to derive the $K$-band luminosity function for both early- and later type galaxies. We can compare ours with those of Kochanek et al. (2001). Since both samples have very bright limiting magnitudes, $K < 11.2$ for Kochanek et al. (2001) and $K < 14$ for our sample, the effect of the geometry for the adopted cosmology models cannot make any significant difference in calculating absolute magnitudes at such a low redshift. We can compare the two results directly. In Table 3, we list the $M^*$ and $\alpha$ derived from both our $K < 14$ sample and the 2MASS sample (Kochanek et al. 2001). Our $K$-band luminosity function for early-type galaxies has a similar $M^*$ and $\alpha$ to those of Kochanek et al. (2001), but the luminosity functions for later type galaxies are very different: our $M^*$ is 0.3 mag brighter and our slope is much steeper ($\alpha = -1.42$) than theirs ($\alpha = -0.87$). Steep slopes ($\alpha < -1$) for later type galaxy luminosity functions are also seen in the optical bands (Marzke et al. 1994, 1998; Bromley et al. 1998; Folkes et al. 1999).

The spectrum of the universal luminosity density is another way of testing consistency between optical and infrared luminosity functions (Wright 2001). Dwek et al. (1998) suggested that the spectrum of the universal luminosity density can be fitted by an average spiral galaxy SED (Schmitt et al. 1997). Wright (2001) used the average spiral galaxy SED model to fit the luminosity densities derived from the SDSS luminosity function and found that the model predicts the luminosity densities in the $J$ and $K$ bands should be 2.3 times higher than the values derived from the 2MASS luminosity functions. In Figure 5, we reproduce the luminosity density plots by adding our points. Our $K$-band

### Figure 4

Our luminosity function is plotted against two 2MASS $K$-band luminosity functions (Cole et al. 2001; Kochanek et al. 2001) and those of Gardner et al. (1997) and Szokoly et al. (1998). We also plot our luminosity function for $z < 0.1$, which is consistent with those from the 2MASS sample.

### Table 3

| Sample                  | Early Type | Later Type |
|-------------------------|------------|------------|
|                         | $M^*$      | $\alpha$   | $M^*$      | $\alpha$   |
| Kochanek et al. 2001    | $-23.53 \pm 0.06$ | $-0.92 \pm 0.10$ | $-22.98 \pm 0.06$ | $-0.87 \pm 0.09$ |
| This paper              | $-23.56 \pm 0.26$ | $-1.03 \pm 0.31$ | $-23.28 \pm 0.28$ | $-1.42 \pm 0.31$ |

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luminosity density is about 2 times higher than those derived from the 2MASS samples (Cole et al. 2001; Kochanek et al. 2001), much closer but still lower than what the model predicts. The luminosity density of our subsample with z < 0.1 is consistent with those from the 2MASS sample. This is not surprising since they are derived using similar luminosity functions. Our luminosity density for the K < 15 sample is measured at a mean redshift of z/C24/0.1, comparable to SDSS and 2dFGRS optical samples. However, the 2MASS (SDSS, 2dFGRS) paired catalogs are much shallower, z ~ 0.05, so it seems that the most likely explanation is that 2MASS is sampling a local underdensity in the galaxy distribution. However, it is now clear that at a redshift ~0.15, there is no broad mismatch in optical and infrared luminosity densities. We also notice that in the model, the average spiral galaxy SED (Schmitt et al. 1997) plus a constant tail (fν ∝ ν−2) at short wavelength (Dwek et al. 1998; Wright 2001) does not fit the luminosity densities well in detail, either.

5. CONCLUSIONS

We present a large and highly complete large K-selected redshift sample down to K ≤ 15 and use it to derive the K-band luminosity function using both non-parametric and STY methods. In comparison to previous K-band luminosity functions, our K-band luminosity function has a significantly brighter characteristic luminosity and steeper slope. The slope is the same as in the optical determinations. The K-band luminosity density measured from our sample is 2 times higher than those measured from the 2MASS redshift sample, the largest local K-selected redshift sample. We argue that this deeper survey, of comparable depth to the optical and SDSS surveys, is more strictly comparable in luminosity density and that we have, in fact, resolved the discrepancy of the 2MASS survey. We are also able to reproduce the 2MASS K-band luminosity function using similar subsample with z < 0.1.

We also derive the K-band luminosity functions for both early- and later type galaxies. The early-type galaxies have a bright M* and a flat slope α ~ −1, while the later type galaxies have a faint M* and a steep slope α = −1.4. A steep slope for later type galaxies is also found in the current large optical redshift surveys.

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