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A WIDE-FIELD *K*-BAND SURVEY: THE LUMINOSITY FUNCTION OF GALAXIES

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ABSTRACT

We present the first determination of the near-infrared *K*-band luminosity function of field galaxies from a wide-field *K*-selected redshift survey. The best-fit Schechter function parameters are $M^* = -23.12 + 5 \log h$, $\alpha = -0.91$, and $\phi^* = 1.66 \times 10^{-2} h^3$ Mpc^{-3}. We estimate that systematics are no more than 0.1 mag in M^* and 0.1 in α, which is comparable to the statistical errors on this measurement.

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

1. INTRODUCTION

The luminosity function of galaxies is central to many problems in cosmology, including the interpretation of faint number counts. Because of this, the faint-end slope of the luminosity function is currently the subject of much debate. Most measurements of the optical luminosity function of field galaxies show a flat slope, corresponding to $\alpha \approx -1.0$ in the Schechter (1976) parameterization (Efstathiou, Ellis, & Peterson 1988; Loveday et al. 1992; Lin et al. 1996; but see Marzke, Huchra, & Geller 1994). Deep field galaxy surveys, on the other hand, detect a very steep slope for the faint end of the optical number count relation, at the point where the relation could be dominated by the faint-end slope of the local luminosity function (Tyson 1988; Lilly, Cowie, & Gardner 1991; Metcalfe et al. 1996; but see also Cowie et al. 1996).

The near-infrared provides several advantages over the optical for statistical studies of galaxies. The *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. The *K* band is dominated by near–solar-mass stars, which make up the bulk of the galaxy. The absolute *K* magnitude is a measure of the visible mass in a galaxy, and thus the *K*-band luminosity function is an observational counterpart of the mass function of galaxies. Previous determinations of the local *K*-band luminosity function have suffered from small sample size or color-dependent incompleteness (Mobasher, Sharples, & Ellis 1993; Glazebrook et al. 1995), while surveys conducted at fainter levels are more appropriate for studying the evolution of galaxies (Songaila et al. 1994; Cowie et al. 1996). In general, studies of galaxy evolution through number counts, colors, redshift distributions, and clustering properties all require an understanding of the local population of galaxies for interpretation of the faint-end data.

We have conducted a photometric and spectroscopic survey of galaxies, observed in the near-infrared and optical with linear detectors, and have obtained spectroscopic redshifts for a sample of galaxies selected in the near-infrared. We present here the *K*-band luminosity function. Results of the photometry were presented in Gardner et al. (1996, hereafter Paper I) and Baugh et al. (1996, hereafter Paper II). Future papers in this series will present the catalog, an analysis of the redshift and color distributions of the galaxies, the bivariate optical–near-infrared luminosity function of galaxies, and an analysis of the star counts.

2. THE LUMINOSITY FUNCTION

The luminosity function of galaxies is the volume density of galaxies as a function of their absolute magnitude. Field galaxy surveys such as this one are typically magnitude limited, and the galaxy distribution has structure along the line of sight of the survey. Several methods have been developed to determine the luminosity function from a redshift survey, avoiding systematics due to clustering. Reviews are presented in Binggeli, Sandage, & Tammann (1988) and Efstathiou, Ellis, & Peterson (1988, hereafter EEP).

The traditional method for determining the luminosity function from a magnitude-limited field galaxy redshift survey is to sum over the inverse of the maximum volume within which each galaxy could have been detected (Felten 1977), but this method is biased because of clustering of the galaxies. Sandage, Tammann, & Yahil (1979, hereafter STY) developed a maximum likelihood technique for fitting a parametric form, in which the effects of clustering cancel out on the assumption that the luminosity function does not depend on position. EEP developed the stepwise maximum likelihood method (SWML) in which the data are binned, but the results are relatively insensitive to clustering and no parametric form is assumed. Other workers extended these methods to include the effects of photometric errors (Loveday et al. 1992), redshift errors (SubbaRao et al. 1996), peculiar motions (Schechter 1976), substantially incomplete data sets (Isobe & Feigelson 1992), and the use of likelihood to measure the goodness of fit of a parametric form (Yahil et al. 1991).

2.1. *The Data*

We have conducted a spectroscopic redshift survey of galaxies selected on the basis of their *K*-band flux in an area of

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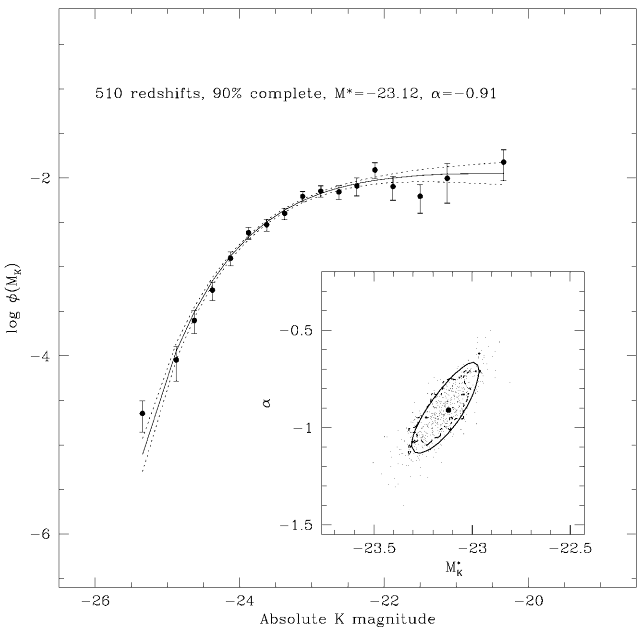

FIG. 1.—The differential K-band luminosity function of galaxies. The points and their errors were determined from our data using the SWML method of EEP. The solid line is the best-fit Schechter function determined using the STY maximum likelihood method. The dashed lines show the effect of varying the parameters of the fit by $\pm 1\ \sigma$, as determined from the error ellipse. Inset are the error ellipse on the Schechter parameter fit to the luminosity function, and the results of 1000 Monte Carlo simulations of our survey parameters. These simulations were binned as 0.03 in M^* and 0.03 in α, and a contour containing 68% (i.e., 1 σ) of the points in the binned data is shown as a dashed line.

approximately 4.4 deg^2, from within a larger photometric survey of 10 deg^2. The photometric observations in two fields of roughly equal area were made in the K band with a HgCdTe detector in 1994 June on the Kitt Peak National Observatory (KPNO) 1.3 m telescope, and in the B, V, and I bands with a 2048^2 CCD camera in 1995 June on the KPNO 0.9 m telescope. In 1996 May, we used the 4.2 m William Herschel Telescope (WHT) on La Palma, with the Autofib-2 fiber positioner and the WYFFOS spectrograph, to obtain spectra of 567 objects selected at $K < 15$. Approximately 75% of the spectroscopic observations were made in the NGP field, and the remainder were made in the NEP field (see Paper II). Objects within the photometric sample were selected for spectroscopy on purely geometrical criteria determined by the characteristics of Autofib-2. There is a small bias against interacting galaxies, since fibers could not be placed closer than 30″ apart. The data reduction was done with the WYFRED package written by Jim Lewis at the Royal Greenwich Observatory, and the redshift identification was done with software developed by Karl Glazebrook. We obtained good identifications and redshifts of 465 galaxies in the sample and less certain redshifts for an additional 45 galaxies. The latter have spectra with poor signal-to-noise ratios, poor sky subtraction, or only a single significant line or break. Three objects were identified spectroscopically as stars. The remaining 54 galaxies were unidentified, giving a completeness of 90%.

2.2. *Determination of the Luminosity Function*

We calculated the luminosity function from our data using the SWML method. The results are plotted in Figure 1. We determined the variances using the constraint given in EEP, with $M_{\rm fid} = -23.5 + 5 \log h$ and $\beta = 1.5$. We used the STY maximum likelihood method to determine the best-fit Schechter function parameters, $M^* = -23.12 + 5 \log h$ and $\alpha = -0.91$, and this function is plotted as a solid line in Figure 1, with the error ellipse in M^* and α plotted in the inset. The dashed lines on either side of the Schechter function in Figure 1 show the effect of varying M^* and α by $\pm 1\ \sigma$. As a check of our error determinations, we ran 1000 Monte Carlo simulations of the survey. Using a number count model, we assigned redshifts and absolute magnitudes to a mock sample of 510 galaxies selected at $K < 15$, and we determined the Schechter parameters using the STY method. These 1000 simulations are plotted in the inset to Figure 1. The contour enclosing 68% of the points agrees approximately with the error ellipse determined from the likelihood. The mean parameter values from the 1000 simulations differed from the inputs by -0.03 mag in M^* and by -0.01 in α, and this may be taken as an indication of systematic errors in the techniques used, and of the inaccuracy in the number count model.

Errors in the photometry affect the determination of the luminosity function. Our K-band photometry is accurate to about 0.1 mag at the selection limit of $K = 15.0$. The steep slope of the number counts at this magnitude will result in more galaxies scattering into the sample from fainter magnitudes than scattering out of the sample. We investigated this effect with 1000 Monte Carlo simulations. We created a mock catalog limited at $K < 15.5$, added Gaussian noise with $1\ \sigma = 0.10$, selected a new $K < 15.0$ catalog, and determined the corresponding Schechter function parameters. The mean results of these simulations differed from the input parameters by only -0.04 mag in M^* and by -0.04 in α.

K-corrections are relatively independent of Hubble type in the K band, but nonetheless we used the method of Eales (1993), described by Gardner (1996), to determine the types. We adopted models for the $B - V$, $V - I$, and $I - K$ colors as a function of redshift from five Bruzual & Charlot (1997, hereafter GISSEL96) solar metallicity models with different star formation histories. A least-squares fit to the colors of the galaxies provided the rest-frame spectral energy distribution, which was convolved with the filter response function to obtain the rest-frame absolute K magnitude. Our goal is to measure the zero-redshift luminosity function of galaxies, and so we included the effects of passive evolution (that is, E-corrections), in our fits and in the determination of the luminosity function. The best-fit Schechter parameters, including K-corrections but ignoring the effects of passive evolution, are given in Table 1. The difference in M^* measured in these two cases reflects the evolution of an elliptical galaxy from the median redshift of the survey ($z = 0.14$) to the present, which is $\Delta M_K = -0.17$ in the GISSEL96 model.

TABLE 1

THE DEPENDENCE OF THE SCHECHTER PARAMETERS ON COSMOLOGICAL GEOMETRY AND EVOLUTIONARY CORRECTIONS

q_0	Corrections	$M^* - 5 \log (h)$	α	$\phi^* h^{-3}$
0.5	K & E	−23.12	−0.91	1.66×10^{-2}
0.5	K only	−23.37	−1.03	1.82×10^{-2}
0.02	K & E	−23.30	−1.00	1.44×10^{-2}
0.02	K only	−23.51	−1.09	1.50×10^{-2}

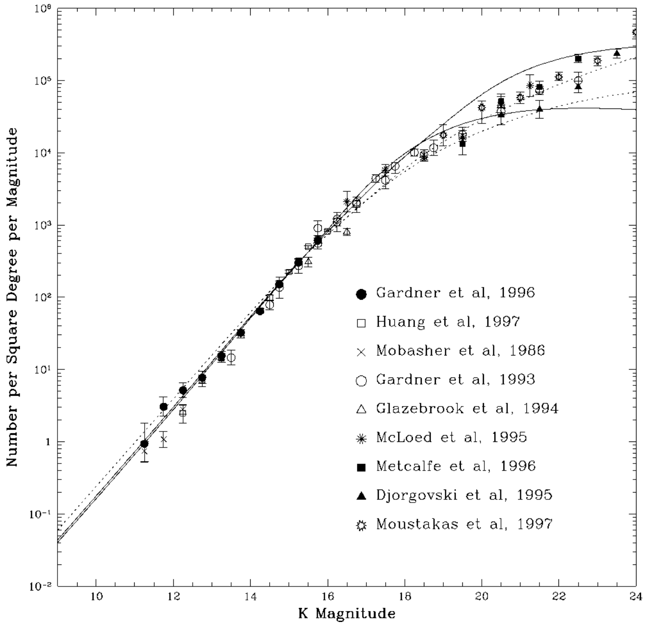

FIG. 2.—The *K*-band number counts compared with models based upon our estimated luminosity functions. The solid lines include the effects of passive evolution, while the dotted lines include only *K*-corrections. The higher line in each case is for $q_0 = 0.02$, while the lower lines are for $q_0 = 0.5$.

Throughout this paper we have used a cosmology in which $H_0 = 100\ h$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$, and $\Lambda = 0$. Varying q_0 affects the calculation of absolute magnitude and the evolutionary model. The best-fit Schechter functions for $q_0 = 0.02$ are listed in Table 1. The difference in M^* between the flat and open cosmologies may be compared with $\Delta M_K = -0.13$, which is the difference in the absolute magnitudes of an elliptical galaxy at the survey median redshift when calculated in the two different cosmologies.

2.3. *The Normalization* ϕ^*

The STY and SWML methods determine the shape of the luminosity function, but not its normalization (ϕ^* in the Schechter parameterization). This can be obtained directly from the redshift data (see Loveday et al. 1992), but it is better to use the number counts from the largest available photometric survey. Our photometric survey covers 10 deg^2, and the number counts have been confirmed by the results of Huang et al. (1997). We therefore follow Mobasher et al. (1993), and determine ϕ^* using a model of the *K*-band number counts based on our estimated values of M^* and α. The model is described in Paper I, but we have used the distribution of spectral types (and thus star formation history within the GISSEL96 models) determined by the methods discussed above. We plot in Figure 2 a compilation of the *K*-band number counts, along with our model predictions based upon the values of M^* and α listed in Table 1. The normalization for each model was determined by a least-squares fit to the number counts from Paper I and is listed in Table 1.

2.4. *The Effects of Incompleteness*

We consider here possible biases arising from the 10% of the objects for which we attempted spectroscopy, but failed to secure an identification. We used a two-sample Kolmogorov-Smirnov test to determine whether the identified and unidentified galaxies are drawn from the same population. The two samples are not different at the 3 σ level in $I - K$ color or $B - K$ color, but do differ in their apparent *K*-magnitude distribution since the unidentified galaxies are mostly at the faint end. They are also different in *I*-band central surface brightness, but this is primarily because of the different distributions in apparent magnitude in the two samples. There was no significant difference between the two samples in the quantity central surface brightness minus total magnitude, as measured in the *I* band. The *K*-band central surface brightness is more difficult to measure because of the large (2″) pixels used, but this is a less relevant quantity since we used optical spectroscopy to identify the galaxies.

The unidentified galaxies are mainly at the faint end, as every galaxy with $K < 13.25$ was identified. To test whether this apparent magnitude selection significantly affects the measured luminosity function, we reran the Monte Carlo simulation discussed above, this time creating a mock catalog of 564 galaxies in each simulation. From this mock catalog we removed 54 galaxies with the same apparent magnitude distribution as the unidentified galaxies in our survey. We repeated this process 1000 times, and the mean results of this simulation differed from the input parameters by -0.04 mag in M^* and by $+0.04$ in α. This is less than the rms statistical error, but represents the possible systematic error due to incompleteness. We estimate the total systematic error due to incompleteness and photometric errors within the spectroscopic catalog to be less than 0.1 mag in M^* and less than 0.1 in α. The effects of possible incompleteness in the photometric catalog due to surface brightness or other effects are beyond the scope of this paper and will be considered elsewhere (Gardner et al., in preparation).

3. DISCUSSION

We have presented the first determination of the *K*-band luminosity function of field galaxies from a wide-field *K*-band selected spectroscopic redshift survey. Our completeness of 90% is comparable to that of optically selected surveys, and we estimate that the systematic errors due to incompleteness and photometric errors are smaller than the statistical errors because of the number of galaxies in our sample.

Previous determinations of the *K*-band luminosity function were based on *K*-band photometry of an optically selected redshift survey (Mobasher et al. 1993) and on a redshift survey of a small number of galaxies selected in the *K* band (Glazebrook et al. 1995). In Figure 3 we compare our results with these two other determinations. Following Glazebrook et al. (1995), we apply a correction of $+0.22$ mag to the Mobasher et al. (1993) measurement to account for their method of calculating *K*-corrections, and an aperture correction of -0.30 to the Glazebrook et al. (1995) measurement. In the inset to the figure we plot the error ellipse of the STY determination of the Schechter function parameters for our measurement of the luminosity function and the error ellipse from the measurement of Mobasher et al. (1993). Glazebrook et al. (1995) fixed α at -1.0 and determined M^*; their error estimate is plotted as an error bar in the inset figure. The errors of the three determinations overlap at better than the 1 σ level. All three determinations are consistent with a flat faint-end slope of -1.0, similar to that determined from most optical surveys.

Optical surveys reveal an excess of faint blue galaxies over

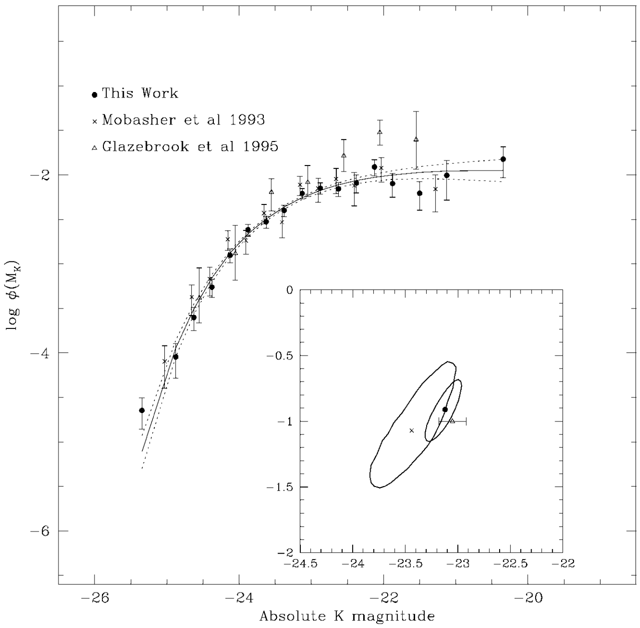

FIG. 3.—Our measurements of the K-band luminosity function from Fig. 1 compared to previous measurements by Mobasher et al. (1993) and Glazebrook et al. (1995). The errors in the Schechter function parameter determinations are inset, showing the best-fit values of Mobasher et al. (1993) (*cross*), our measurement (*solid dot*), and the fit of Glazebrook et al. (1995) as an error bar since they fixed the value of α in their determination. We have applied corrections of $+0.22$ mag and -0.30 mag to the Mobasher et al. (1993) and Glazebrook et al. (1995) measurements, respectively (see text).

and above the number predicted by simple models relating local to distant observations (e.g., Tyson 1988; Lilly et al. 1991). The flat faint-end slope measured in the local B-band luminosity function of galaxies (EEP; Loveday et al. 1992) plays an important role in this interpretation, for the faint blue galaxies might otherwise be explained by a local population of intrinsically faint galaxies. Surveys selected in the K band preferentially study normal, massive galaxies. The simple passive-evolution number count models in Figure 2 fit the observed counts well at $K < 18$, and the faint blue galaxy population does not dominate the color distributions until fainter than this (Gardner 1995). K-band surveys present a different picture from optical surveys. Instead of rapid evolution at intermediate or even low redshifts, the counts and colors of the galaxies making up the K-band surveys show only passive evolution of the old stellar population to $z{\sim}0.5$.

The data and software used in this paper are available in electronic form upon request from the authors.

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