THE EVOLUTION OF THE OPTICAL AND NEAR-INFRARED GALAXY LUMINOSITY FUNCTIONS AND LUMINOSITY DENSITIES TO $z \sim 2$

TOMAS DAHLEN, 1,2 BAHRAM MOBASHER, 1,3 RACHEL S. SOMERVILLE, 1 LEONIDAS A. MOUSTAKAS, 1 MARK DICKINSON, 3 HENRY C. FERGUSON, 1 AND MAURO GIVALISCO 1

Received 2004 October 20; accepted 2005 May 15

ABSTRACT

Using Hubble Space Telescope and ground-based $U$ through $K_s$ photometry from the Great Observatories Origins Deep Survey, we measure the evolution of the luminosity function and luminosity density in the rest-frame optical ($U$, $R$, and $R$) to $z \sim 2$, bridging the poorly explored “redshift desert” between $z \sim 1$ and $z < 2$. We also use deep near-infrared observations to measure the evolution in the rest-frame $J$ band to $z \sim 1$. Compared to local measurements from the SDSS, we find a brightening of the characteristic magnitude, $M^*$, by $\sim 2.1$, $\sim 0.8$, and $\sim 0.7$ mag between $z \sim 0.1$ and $z \sim 1.9$, in $U$, $B$, and $R$, respectively. The evolution of $M^*$ in the $J$ band is in the opposite sense, showing a dimming between redshifts $z \sim 0.4$ and 0.9. This is consistent with a scenario in which the mean star formation rate in galaxies was higher in the past, while the mean stellar mass was lower, in qualitative agreement with hierarchical galaxy formation models. We find that the shape of the luminosity function is strongly dependent on spectral type and that there is strong evolution with redshift in the relative contribution from the different spectral types to the luminosity density. We find good agreement with previous measurements, supporting an increase in the $B$-band luminosity density by a factor of $\sim 2$ between the local value and $z \sim 1$, and little evolution between $z \sim 1$ and $z \sim 2$. We provide estimates of the uncertainty in our luminosity density measurements due to cosmic variance. We find good agreement in the luminosity function derived from an $R$-selected and a $K_s$-selected sample at $z \sim 1$, suggesting that optically selected surveys of similar depth ($R \leq 24$) are not missing a significant fraction of objects at this redshift relative to a near-infrared–selected sample. We compare the rest-frame $B$-band luminosity functions from $z = 0$ to 2 with the predictions of a semianalytic hierarchical model of galaxy formation and find qualitatively good agreement. In particular, the model predicts at least as many optically luminous galaxies at $z \sim 1–2$ as are implied by our observations.

Subject headings: galaxies: distances and redshifts — galaxies: evolution — galaxies: fundamental parameters — galaxies: high-redshift — galaxies: luminosity function, mass function

1. INTRODUCTION

The luminosity function (LF) is one of the most fundamental metrics of the galaxy population and is essential for characterizing statistical properties of galaxies and their evolution. Studying the LF as a function of cosmic epoch, galaxy type, and environment provides insights into the physical processes that shape galaxies. The measured parameters of the LF—the normalization, faint-end slope, and location of the characteristic luminosity or “knee”—are strong constraints on galaxy formation models and indeed are often considered the most basic test of a model’s viability. When integrated over all luminosities, the LF provides a measure of the global luminosity density. The dependence of this quantity on wavelength and cosmic time allows us to probe the cosmic star formation and stellar mass assembly rate.

To construct the LF, we require a complete and unbiased sample of galaxies to a given flux limit, with well-known selection functions and available redshifts. At any given redshift, the survey should probe a volume large enough to control cosmic variance and should contain enough galaxies in each magnitude bin to minimize Poisson noise. Recently, these problems have been largely overcome for measures of the local LF ($z \sim 0$) by several wide-area, multi–wave band surveys with follow-up spectroscopy. Recent local surveys include the Two Degree Field Galaxy Redshift Survey (2dF GRS; Colless et al. 2001; Norberg et al. 2002), the Sloan Digital Sky Survey (SDSS; Stoughton et al. 2002; Blanton et al. 2001, 2003), and the Two Micron All Sky Survey (2MASS; Jarrett et al. 2000; Kochanek et al. 2001; Cole et al. 2001). These studies have resolved the debate about the normalization and faint-end slope of the local optical LF that persisted for many years (Marzke et al. 1994; da Costa et al. 1994; Lin et al. 1996).

In order to study the LF at high redshift, as is our goal here, the desire for wide-area coverage and large samples must be balanced against the need for photometry deep enough to probe faintward of the knee in the LF ($L_\kappa$). In addition, in order to construct the high-redshift LF in a given fixed rest wavelength, we require photometry at wavelengths longward of the desired rest frame. Obtaining measures of the rest-frame optical LF at redshifts above $z \sim 1$ has therefore proved challenging, because of the difficulty of obtaining deep near-infrared (hereafter NIR) photometry over fields large enough. Obtaining spectroscopic redshifts for LF studies at high redshift is also extremely challenging. Most previous studies of the LF out to $z \sim 1$ that are based on spectroscopic surveys, such as the Canada-France Redshift Survey (Lilly et al. 1995), CNOC2 (Lin et al. 1999) and the Caltech Faint Galaxy Redshift Survey (Cohen 2002), represent heroic efforts but were seriously limited by small number statistics and uncertainties due to cosmic variance. Two major efforts exploiting
multiobject spectrographs on large telescopes are directed toward obtaining redshifts for significant volumes out to $z \sim 1.5$ and will greatly improve this situation: the DEEP2 redshift survey on the Keck telescope (Davis et al. 2003) and the VIMOS-VLT Deep Survey (V VDS; Le Févre et al. 2005). See also the Team Keck Treasury Redshift Survey (Wirth et al. 2004). However, even these surveys are optically (R band) selected and may suffer incompleteness for faint and/or red objects at $z \gtrsim 1$.

An alternative and powerful method of obtaining redshifts for statistically large samples to deep flux levels is provided by the photometric redshift method, analogous to low-resolution spectroscopy. Due to improved accuracy in photometric redshift techniques in recent years [$\Delta z \equiv \langle |z_{\text{photon}} - z_{\text{spec}}|/(1 + z_{\text{spec}}) \rangle \lesssim 0.1$; Benitez 2000; Mobasher et al. 2004], sufficiently reliable redshifts are now available for statistical studies of galaxies. Large, deep multi–wave band surveys using photometric redshifts to measure LFs to $z < 1.5$ have recently been completed by, e.g., the Las Campanas Infrared Survey (Chen et al. 2003) and the COMBO-17 project (Wolf et al. 2003). To higher redshifts ($z < 3$–5), but for relatively smaller areas, LFs have been presented by, e.g., the Subaru Deep Survey (Kashikawa et al. 2003), the FORS Deep Field (Gabasch et al. 2004), and Poli et al. (2003).

In this paper, we make use of observations obtained as part of the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) in the Chandra Deep Field South (CDF-S), also known as the GOODS-S field. We combine the results from a wider area ($\sim 1100$ arcmin$^2$), optically selected ($R_{\text{AB}} < 24.5$) catalog with those of a smaller area ($\sim 130$ arcmin$^2$) but very deep NIR-selected ($K_{\text{AB}} < 23.2$) catalog to measure galaxy luminosity functions and the luminosity density from $z \sim 0.1$ to 2. Using the optically selected sample, we construct these quantities from $z \sim 0.1$ to 1 for the overall galaxy population and for different spectral types. The NIR-selected catalog represents an unprecedented combination of area and depth, allowing us to probe deeper down the rest-frame optical luminosity function in the difficult “spectroscopic desert” regime of $z \sim 1$–2 than has been possible. We construct the rest-frame optical LF to $z \sim 2$ using the $K_{\text{S}}$-selected catalog. We also use the $K_{\text{S}}$-selected catalog to determine the evolution of the rest-frame J-band LF to $z \sim 1$.

In § 2, we present the multi–wave band data set used in this study and the technique used to estimate photometric redshifts. The methods used to measure the LFs, incorporating photometric redshift errors using the redshift probability distributions, and our approach for estimating the uncertainty due to cosmic variance are discussed in § 3. In § 4 we present our measurements of the LF from $z \sim 0.1$ to 2 for the global population and the LF divided by spectral type and compare our results with the predictions of a semianalytic model of galaxy formation. We use these results to derive the integrated luminosity density from $z \sim 0.1$ to 2. We discuss our results and conclude in § 5.

Throughout this paper we adopt a flat cosmological constant–dominated cosmology ($\Omega_{\Lambda} = 0.7$ and $\Omega_{m} = 0.3$) and a Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. All magnitudes are in the AB system (Oke & Gunn 1983).

2. MULTI–WAVE BAND DATA AND PHOTOMETRIC REDSHIFTS

The photometric data for the CDF-S were obtained using ground-based optical and NIR observations from the European Southern Observatory (ESO; 2.2 m Wide Field Imager [WFI], VLT-FORS1, NTT-SOFI, and VLT-ISAAC) and Cerro Tololo Inter-American Observatory (CTIO; 4 m telescope) covering U, B, V, R, I, J, H, and $K_{\text{S}}$, as well as space-based Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) observations in BViz. A summary of the observations and data reduction is given in Giavalisco et al. (2004). For the purpose of this study, two different photometric catalogs were produced. Using SExtractor (Bertin & Arnouts 1996), we constructed a WFI R band–selected catalog, including all ground-based photometry, and an ISAAC $K_{\text{S}}$ band–selected catalog, including ISAAC J, H, and $K_{\text{S}}$ and ACS BViz photometry. The R-selected catalog covers $\sim 1100$ arcmin$^2$, while the $K_{\text{S}}$-selected catalog covers $\sim 130$ arcmin$^2$. Magnitudes used for calculating LFs are based on SExtractor MAG-AUTO, while colors used for determining photometric redshifts and spectral types are based on 3$^\text{rd}$ magnitude to select against wrongly assigned photometric redshifts, an approach used by, e.g., COMBO-17 (Wolf et al. 2003). As part of the procedure for estimating the photometric redshift of individual galaxies by fitting the observed SEDs to templates, the apparent magnitude limits are $R = 24.5$ and $K_{\text{S}} = 23.2$, resulting in 18,381 galaxies at $0.1 < z < 1.0$ and 2768 galaxies at $0.1 < z < 2.0$ for the $R$- and $K_{\text{S}}$-selected catalogs, respectively. The magnitude limits are sufficiently bright ($\sim 0.5$ mag brighter than the magnitude at which the number counts start to deviate from a pure power law) to allow accurate photometric redshifts estimates and yet faint enough to make it possible to study the evolution of the faint end of the LF, as well as the integrated luminosity density, for a major part of the galaxy population.

Using the available 13 ($R$-selected catalog) and 7 ($K_{\text{S}}$-selected catalog) passbands, we estimate photometric redshifts for all galaxies in this survey to the magnitude limits given above. The photometric redshift code developed for this investigation is based on a template-fitting method (e.g., Gwyn 1995; Mobasher et al. 1996) and includes a Bayesian prior based on an input LF similar to the approach used in, e.g., Kodama et al. (1999) and Dahlen et al. (2004). At each redshift, the absolute $I$-band magnitude of the object is calculated and compared to an input LF. The main effect of the absolute magnitude prior is to discriminate between cases in which the $\chi^2$ fitting results in two probability peaks due to confusion between the Lyman break and the 4000 Å break. The absolute magnitude that the object would have at the two redshift peaks can discriminate between the choices; i.e., an absolute magnitude significantly brighter than $M^*$ is regarded as increasingly improbable. This prior is similar to the method of using a single bright-magnitude cutoff for the absolute magnitude to select against wrongly assigned photometric redshifts, an approach used by, e.g., COMBO-17 (Wolf et al. 2003).

In most cases, however, the prior does not affect the results, and the photometric redshift is given by the best $\chi^2$ fit. Note also that we use a flat faint-end slope for the input prior LF. This is equivalent to not imposing any luminosity prior at all at faint magnitudes. This is important since we do not want to bias the slope of the LF that we later measure using the results from the photometric redshifts. Absorption due to intergalactic H i is included using the parameterization in Madau (1995). We use the four different template spectral energy distributions (SEDs), consisting of E, Sbc, Sed, and Im, from Coleman et al. (1980), extended to UV and IR wavelengths by Bolzonella et al. (2000). We also include two starburst templates from Kinney et al. (1996; SB2 and SB3). Ten additional templates are constructed by interpolating between subsequent SEDs.
we also obtain the spectral type and the redshift probability distribution for each galaxy. These SED types are used in the following sections to study the evolution of the LFs for galaxies of different spectral types, while the redshift probability distribution for each galaxy is used to incorporate the errors in the photometric redshifts, which propagate through the estimated LFs (§ 3.1).

We divide the galaxies into three broad spectral types; early type, late type, and starburst. Galaxy types with a best-fitting SED dominated by the elliptical spectrum are defined as early types, while those dominated by one of the spiral galaxy spectra are called late types. Starbursts are best fitted by one of the two starburst spectra. The approximate division between types in rest-frame color is that objects with $B - V > 0.7$ are early types and that objects with $B - V < 0.25$ are starbursts, while objects with intermediate color are late types.

Note that the spectral types, which we here divide into early type, late type, and starburst, represent the average color of the galaxies. These do not necessarily have a one-to-one correlation to morphological types, e.g., morphological elliptical galaxies, spiral galaxies, and irregular galaxies. At least at moderate redshifts, however, the correlation appears to be strong.

In Figure 1, we show the absolute magnitude versus redshift relation for the $R$ band– and $K_s$ band–selected samples. The early-type, late-type, and starburst galaxies are represented by red, green, and blue, respectively. Absolute magnitudes are calculated according to the recipe described in § 3.

3. METHOD

In this section we present the technique used to estimate the LF and our procedure for accounting for the errors in our photometric redshifts. We also describe our approach for estimating the uncertainty in our results due to cosmic variance.

3.1. Deriving the Luminosity Function

Using the information on photometric redshift and best-fitting SED template, we calculate the rest-frame absolute magnitude in

Fig. 1.—Rest-frame $B$-band magnitude vs. redshift for the $R$-selected sample (top) and the $K_s$-selected sample (bottom), showing galaxies with early (red dots), late (green dots), and starburst (blue dots) spectral types.
filter $Y$, $M_Y$, from the observed apparent magnitude in filter $X$, $m_X$, using the general equation

$$M_Y = m_X - 5 \log(D_L(z)/10 \text{ pc}) - K_{XY}(z, T), \quad (1)$$

where $K_{XY}(z, T)$ is the $K$-correction at redshift $z$ for template type $T$, correcting from observed filter $X$ to rest-frame filter $Y$, and $D_L(z)$ is the luminosity distance. A detailed description of how we calculate rest-frame magnitudes and the luminosity distance is given in the Appendix.

We use the $1/V_{\text{max}}$ method (Schmidt 1968) to calculate the LF according to

$$\Phi(M) dM = \frac{1}{V_i(M_i)}, \quad (2)$$

where $V_i(M_i)$ is the observable comoving volume in which a galaxy $i$ with absolute magnitude $M_i$ is detectable, when we consider the apparent magnitude and redshift limits of the survey. The sum is taken over all galaxies in the magnitude range $M - \Delta M/2 < M_i < M + \Delta M/2$. When evaluating equation (2), we set $\Delta M = 0.5$ mag. The comoving volume for any given galaxy is given by the redshift range $z_{i,\text{min}} - z_{i,\text{max}}$, where $z_{i,\text{min}} = \max(z_{\text{low}}, z_{\text{min}})$ and $z_{i,\text{max}} = \min(z_{\text{high}}, z_{\text{max}})$. Here $z_{\text{low}}$ and $z_{\text{high}}$ are the lower and upper redshift limits of the redshift bin where the LF is determined and $z_{\text{min}}$ and $z_{\text{max}}$ are the redshift limits at which a galaxy with absolute magnitude $M_i$ would have an apparent magnitude within the magnitude limits of the survey. For a survey covering an area $\Delta \Omega$, the volume becomes

$$V_i = \frac{c \Delta \Omega}{H_0} \int_{z_{i,\text{min}}}^{z_{i,\text{max}}} D_L(z)^2 \left[ \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{\Lambda} \right]^{-1/2} dz, \quad (3)$$

where $\Omega_k = 1 - \Omega_m - \Omega_{\Lambda}$, $H_0$ is the Hubble constant, $c$ is the speed of light, and $D_L$ is the luminosity distance (see the Appendix). The $1/V_{\text{max}}$ method does not assume any underlying parametric form for the LF. Instead, after determining the number of objects in each magnitude bin (and their errors), it is possible to fit any desired functional form to the data. A drawback of the $1/V_{\text{max}}$ method is that systematic biases may be introduced by large-scale fluctuations and clustering within the observed field (de Lapparent et al. 1989).

Deriving the LF requires determination of the absolute magnitude of each galaxy. With redshifts estimated from photometric redshift methods, the relatively large errors in redshifts propagate to errors in the luminosity distances and $K$-corrections and therefore also to the absolute magnitudes.

As faint galaxies are much more abundant than bright ones, a larger fraction of intrinsically faint galaxies are shifted to the bright end than the fraction of intrinsically bright galaxies that are moved to the faint end (Chen et al. 2003). Thus, uncertainties in the redshifts may introduce biases in the determination of the LF and lead to systematic errors when deriving the LF parameters, e.g., in determining the characteristic luminosity and the faint-end slope.

To incorporate the redshift uncertainties, we use for each object its corresponding redshift probability distribution, $p_i(z)$, instead of a single redshift value. The probability distribution is derived from the $\chi^2$ of the template fitting including input priors.

When summing the magnitude bins in equation (2), we use for each object a redshift range $z_- < z < z_+$, where the lower limit, $z_-$, corresponds to $M_i + \Delta M$ and the upper limit, $z_+$, corresponds to $M_i - \Delta M$, as calculated using equation (1). The contribution from each galaxy is weighted by the probability given by

$$p_i = \int_{z_-}^{z_+} p_i(z) dz. \quad (4)$$

This is expressed as

$$\Phi(M) dM = \int \frac{1}{V_i(M_i)} \left[ \int_{z_-}^{z_+} p_i(z) dz \right] dM. \quad (5)$$

Alternatively, the LF can be derived using a maximum likelihood (ML) approach (Sandage et al. 1979). An advantage with the ML method is that it is not as sensitive to large-scale fluctuations as the $1/V_{\text{max}}$ method. On the other hand, the ML method requires fixing the functional form of the LF, which can be misleading since this form is not in general known a priori. Chen et al. (2003) describe a method, analogous to that explained above, for incorporating photometric redshift errors when deriving the LF using the ML method.

### 3.2. Cosmic Variance

An important source of uncertainty in estimates of galaxy densities and related quantities (LF, luminosity density, etc.) in deep fields is the field-to-field variation due to large-scale structure, which is commonly referred to as cosmic variance. It is generally difficult to estimate the magnitude of this variance empirically, as this requires measures of galaxy clustering on scales larger than the field in question and these are generally not available. In Somerville et al. (2004a), we presented an approach for estimating the cosmic variance for observed populations based on the expectations of clustering in the cold dark matter (CDM) theory and a simple model for galaxy bias. These results were appropriate for the variance in the number counts (or number densities) of galaxies discussed in that paper, but are not directly applicable to the variance in the luminosity density, which is of interest here. Because more luminous galaxies presumably occupy more massive dark matter halos and halo clustering is known to be a strong function of mass in the CDM theory, we must account for this in estimating the cosmic variance for mass- or luminosity-weighted quantities such as the luminosity density. We have developed a simple model to address this problem, which we briefly outline here. More details and comparisons with numerical simulations will be given in a future work (J. A. Newman & R. S. Somerville 2005, in preparation).

First, we compute the fractional variance for the underlying dark matter density field in each redshift bin used in our analysis. We approximate the bin geometry as a rectangular solid, as in Newman & Davis (2002), and use the power spectrum for a standard ($n = 1$) ΛCDM cosmology with the same parameters assumed throughout this paper and a normalization of $\sigma_8 = 0.9$. The resulting values of $\sigma_{DM}$, where “DM” indicates “distance modulus,” are given in Table 1 for both the WFI ($R$ selected) and ISAAC ($K_s$ selected) catalog geometries.

Next, we estimate an effective rest $B$-band luminosity-weighted effective bias in the following manner. We assume that the ratio of total halo mass to total $B$-band light as a function of halo mass is given by the functional form

$$\langle M/M_c \rangle = 0.5 \left[ (M/M_c)^{-\gamma_1} + (M/M_c)^{-\gamma_2} \right]. \quad (6)$$
following van den Bosch et al. (2003), and adopt the values for the parameters $\langle M/L \rangle_{0}$, $M_{*}$, $\gamma_{1}$, and $\gamma_{2}$ from their model A. Van den Bosch et al. (2003) showed that this model reproduces the luminosity function and luminosity-dependent clustering of $B$ band–selected galaxies observed locally by the 2dF GRGs. We then define the luminosity-weighted effective bias as

$$b_{\text{Lum}} = \frac{1}{\rho_{\text{Lum}}} \int_{M_{\text{min}}}^{M_{\text{max}}} dn(M, z)/dM \langle M/L \rangle(M) M dM,$$

(7)

where $\rho_{\text{Lum}}$ is the total luminosity density and $dn(M, z)/dM$ is the dark matter halo mass function at redshift $z$. We adopt $M_{\text{min}} = 10^{9}$ $M_{\odot}$. As the light-to-mass ratio declines rapidly with decreasing halo mass, the results do not depend sensitively on $M_{\text{min}}$ as long as it is of this order or smaller. The fractional root variance in the luminosity density is then simply $\sigma_{L} = b_{\text{Lum}} \sigma_{\text{DM}}$.

Note that we assume that the relationship between light and mass $\langle M/L \rangle(M)$ does not change with redshift. This is equivalent to assuming that the halo occupation function does not change with time, so all redshift dependence in our model is contained in the changing dark matter halo mass function and clustering amplitude rather than in the way that galaxies of a given luminosity trace the underlying dark matter halos (e.g., Moustakas & Somerville 2002). It has been shown that this assumption is consistent with observations out to redshifts $z \sim 1$ (Yan et al. 2003; Coil et al. 2004), and the relatively constant luminosity density from $z \sim 1$ to 2 that our observations imply is also consistent with this assumption. Luminous ($L \gtrsim L_{*}$) galaxies must be positively biased ($b > 1$) in the $\Lambda$CDM model considered here, so the variance for the dark matter $\sigma_{\text{DM}}$ probably underestimates the luminosity-weighted variance. If there is evolution in $\langle M/L \rangle(M)$, it is likely to be in the sense that less massive halos contribute a higher fraction of the total luminosity at high redshift than locally (as is found in semianalytic models of galaxy formation), which would tend to decrease our estimate of $b_{\text{Lum}}$. Therefore, the true variance is almost certainly bracketed by $\sigma_{\text{DM}}$ and $\sigma_{L}$. We provide both values in Table 1. We find that the 1 $\sigma$ uncertainty in the dark matter density due to cosmic variance for the WFI ($\sim$1100 arcmin$^2$) fields is $\sim$15%, while the uncertainty in the luminosity density is $\sim$16%–19%. For the smaller ISAAC field ($\sim$130 arcmin$^2$), the DM uncertainty is $\sim$15%–30%, while the luminosity-weighted values are $\sim$16%–45%.

We also note that the empirical relationship between the luminosity and the DM halo mass that we have adopted here is specific to the $B$ band. We expect that this relationship will be qualitatively similar, but perhaps different in detail, in other wave bands. The redshift evolution may also be more pronounced in shorter wave bands (e.g., the $U$ band). Therefore, we do not present cosmic variance estimates for the other wave bands, but we expect that the estimates given for the $B$ band will be fairly representative for the other bands.

4. RESULTS

4.1. Luminosity Functions

In this investigation, we use the $1/V_{\text{max}}$ technique to calculate the LF, which is thereafter fitted to a Schechter function (Schechter 1976). We calculate the rest-frame LFs in the $U$ and $B$ bands using both the $R$-selected (WFI based) and $K_{S}$-selected (ISAAC based) catalogs and calculate the rest $R$ and $J$ band using only the $K_{S}$-selected catalog. We adopt two sets of redshift bins appropriate to the volume and depth of each catalog. The WFI-based rest-frame $U$- and $B$-band and the ISAAC-based $J$-band LFs are each determined in three redshift intervals, $0.1 < z < 0.5$, $0.5 < z < 0.75$, and $0.75 < z < 1.0$. The redshifts corresponding to the volume midpoints of each bin are $z_{0} = 0.39, 0.64,$ and 0.88, respectively (hereafter we use $z_{0}$ to denote this redshift). For the optical bands, we further derive the type-dependent LFs in each bin. For the $J$ band, we do this only for the lowest redshift bin for which statistics are sufficient. Using the $K_{S}$-selected catalog, we extend the determination of the rest-frame $U$-, $B$-, and $R$-band LFs to $z \sim 2$, using six bins with approximately equal comoving volume between $z = 0.1$ and 2. The redshifts of the volume midpoints of these six bins are $z_{0} = 0.62, 0.98, 1.24, 1.48, 1.69,$ and 1.90.

4.1.1. Quasi-Local LFs

In Figures 2–4 (left panels), we show the composite rest-frame $U$-, $B$-, and $J$-band LFs, as well as the type-specific LFs divided into three spectral types: early type, late type, and starburst. The best-fitting Schechter LF parameters ($M_{*}$, $\alpha$, and $\phi$) are listed in Tables 2–4. In Figures 2–4, the error ellipses for the Schechter function parameters for both the total LFs and the different spectral type LFs are presented alongside the LFs. These contours represent 68.3% and 95% confidence intervals and correspond to $\Delta \chi^{2} = 2.3$ and 6.0 above the best-fitting $\chi^{2}$, respectively.

The shape of the LFs varies dramatically between different spectral types. While the late-type LF mainly follows the total LF, showing a fairly steep faint-end slope, the early-type LF has a Gaussian shape, which is significantly flatter at faint magnitudes. There is also an indication of an upturn of the LF at the very faintest magnitudes. We discuss this below. The starburst-type population also has a fairly steep faint-end slope, with number densities of these galaxies at the bright end that are much smaller (by an order of magnitude) than other types.

The composite and type-dependent LFs in the $U$ and $B$ bands are similar, both in terms of the shape and faint-end slopes. There is a difference in that the early-type population is more dominant in $B$ than in $U$, while the opposite is true for the starburst-type population. This difference is more evident in § 4.1.2, where we derive the fractional contribution to the luminosity density from different spectral types.

### Table 1

| Redshift Range
| $V_{\text{com}}$ (Mpc$^{-3}$) | $\sigma_{\text{DM}}$ | $b_{\text{Lum}}$ | $\sigma_{L}$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.1 $< z < 0.5$ | $2.07 \times 10^{7}$ | 0.15 | 1.08 | 0.16 |
| 0.5 $< z < 0.75$ | $3.68 \times 10^{7}$ | 0.16 | 1.17 | 0.19 |
| 0.75 $< z < 1.0$ | $5.42 \times 10^{7}$ | 0.15 | 1.24 | 0.19 |

**Note.**—See § 3.2 for details.

- $a$ Redshift range.
- $b$ Comoving volume corresponding to redshift range.
- $c$ Variance for dark matter halos.
- $d$ Luminosity-weighted effective bias.
- $e$ Variance in luminosity density.
The composite rest-frame $J$-band LF in Figure 4 has an overall shape similar to that of its optical counterparts. In addition, the type-specific LFs have shapes similar to those of the optical. Compared to the optical, especially the $U$ band, the starburst population is relatively fainter in $J$, with the characteristic magnitude of the starburst population being $\sim 3.0$ mag fainter than the composite LF in $J$. In the $U$ and $B$ bands, the difference between the characteristic magnitude of the starburst-type LF and the composite LF is $\sim 1.8$ and $\sim 2.5$ mag, respectively. The early-type population is also more dominant in the $J$ than in the $U$ band. This difference is not significant when comparing the $B$ and $J$ bands. These trends are also reflected in the contribution by different populations to the total luminosity density in different bands, presented in § 4.1.2.

At the faint end of the early-type LF, we note a possible upturn of the LF in all bands (most evident in $B$). A similar result was seen in the LF obtained for early spectral type galaxies from the 2dF GRS (Madgwick et al. 2002). This upturn may be an indication of an abundant population of faint early-type galaxies that starts to dominate the early-type LF at faint magnitudes. This may be analogous to the dwarf elliptical galaxy population that starts to dominate over normal elliptical galaxies in local clusters of galaxies and galaxy groups (e.g., Binggeli et al. 1988). An alternative explanation could be contamination from faint red M stars, whose SEDs are similar to those of early types and may cause confusion, especially at faint magnitudes, where it is more difficult to classify stars using, e.g., PSFs. We will address this issue in a future paper (Dahlen et al. 2005).

The faint-end upturn suggests that a single Schechter function does not provide a good representation of the early-type LF. To investigate how the upturn affects results, we also fit the Schechter parameters after excluding the faint population, similar
to the approach in Madgwick et al. (2002) and Wolf et al. (2003).
Results are given in Tables 1–3. As expected, we find that the faint-end
slope is less steep after excluding the upturn. The effect, however,
is small, mainly because the relative errors at the faint
end are large, giving low weight to these points when deriving
the parameters over the full LF.

In the case of the $J$ band, we note that due to the upturn, it is
possible to fit the LF with a straight line, corresponding to a pure
power law. This is why there is no upper boundary on the early-
type characteristic magnitude in Figure 4 (right).

4.1.2. Luminosity Function Evolution

In Figures 5–7, we show the composite rest-frame WFI-based
$U$- and $B$-band and the ISAAC-based $J$-band LFs in each of the
three redshift bins $0.1 < z < 0.5$, $0.5 < z < 0.75$, and $0.75 < z < 1$. Because we do not reach the same depth at all redshifts,
we have to be careful when studying changes in $M^{*}$ and $\alpha$ with
redshift; i.e., in order to determine $\alpha$, it is desirable to reach at
least $\sim 3$ mag fainter than $M^{*}$. In addition, due to the coupling
between $M^{*}$ and $\alpha$, the determination of $M^{*}$ is affected by the
depth of the survey.

To address this, we use the following two approaches. First,
we fit both $M^{*}$ and $\alpha$ in each redshift interval, using different
limiting absolute magnitudes determined from the complete-
ness in each bin. The resulting best-fitting Schechter functions
are shown as solid red lines in Figures 5–7. Second, we fix the
faint-end slope to that found in the “quasi-local” sample (the
$0.1 < z < 0.5$ bin) and calculate the characteristic magnitude
and normalization in the other redshift intervals. The resulting
Schechter functions are shown as dashed lines in Figures 5–7.

### TABLE 2
Best-fitting Schechter Function Parameters for Rest-Frame $U$-Band Luminosity Functions

| Redshift Range     | $M^{*}_{U} - 5 \log h_{70}$ | $\phi^{*}$  | $\log \rho_{0}$ | Spectral Types |
|--------------------|----------------------------|-------------|-----------------|----------------|
| $0.1 < z < 0.5$    | $-19.98_{-0.08}^{+0.09}$  | $-1.31_{-0.03}^{+0.02}$ | $42.5_{-1.3}^{+1.4}$ | $26.38 \pm 0.03$ | All |
| In Early types     | $-19.71_{-0.14}^{+0.14}$  | $-0.67_{-0.04}^{+0.06}$ | $14.5_{-1.3}^{+1.4}$ | 9.0_{-1.0}^{+1.5} | Early types |
| In Late types      | $-19.66_{-0.16}^{+0.16}$  | $-0.64_{-0.04}^{+0.09}$ | $15.1_{-1.3}^{+1.5}$ | 9.0_{-1.0}^{+1.5} | Late types |
| In Starbursts      | $-20.06_{-0.20}^{+0.20}$  | $-1.39_{-0.04}^{+0.03}$ | $23.9_{-1.3}^{+1.5}$ | 9.0_{-1.0}^{+1.5} | Starbursts |
| $0.5 < z < 0.75$   | $-19.80_{-0.15}^{+0.15}$  | $-0.67_{-0.04}^{+0.06}$ | $44.7_{-1.3}^{+1.4}$ | 9.0_{-1.0}^{+1.5} | Starbursts |
| In Early types     | $-19.44_{-0.12}^{+0.12}$  | $-0.72_{-0.04}^{+0.04}$ | $21.8_{-1.3}^{+1.5}$ | 9.0_{-1.0}^{+1.5} | Early types |
| In Late types      | $-20.24_{-0.10}^{+0.10}$  | $-1.03_{-0.04}^{+0.08}$ | $35.4_{-1.3}^{+1.5}$ | 9.0_{-1.0}^{+1.5} | Late types |
| In Starbursts      | $-19.15_{-0.22}^{+0.22}$  | $-1.23_{-0.04}^{+0.04}$ | $32.0_{-1.3}^{+1.5}$ | 9.0_{-1.0}^{+1.5} | Starbursts |
| $0.75 < z < 1.0$   | $-20.32_{-0.10}^{+0.10}$  | $-1.39_{-0.04}^{+0.07}$ | $38.8_{-1.3}^{+1.5}$ | 9.0_{-1.0}^{+1.5} | Starbursts |
| In Early types     | $-19.74_{-0.24}^{+0.24}$  | $-0.69_{-0.04}^{+0.08}$ | $9.0_{-1.0}^{+1.5}$ | 9.0_{-1.0}^{+1.5} | Early types |
| In Late types      | $-20.47_{-0.12}^{+0.12}$  | $-1.26_{-0.04}^{+0.09}$ | $19.2_{-1.3}^{+1.5}$ | 9.0_{-1.0}^{+1.5} | Late types |
| In Starbursts      | $-19.71_{-0.18}^{+0.18}$  | $-1.31_{-0.04}^{+0.19}$ | $26.8_{-1.3}^{+1.5}$ | 9.0_{-1.0}^{+1.5} | Starbursts |

Notes.—Data are for a $R$ band–selected sample. Luminosity densities are derived by integrating LFs characterized by the best-fitting Schechter function parameters. Errors represent statistical errors. For early types marked with an asterisk, we have excluded the faint upturn at $M_{U} > -16.5$. 
For comparison, we show in the medium- and high-redshift bins the Schechter fit derived in the low-redshift bin as gray lines. Results from the fits are also listed in Tables 2–4.

The characteristic magnitudes in both the U- and B-band LFs become brighter by ~0.3 mag between z = 0.4 and 0.9. For the faint-end slope and the normalization, there is no clear trend with redshift. In the J band, there is an opposite trend in the characteristic magnitude; i.e., it becomes somewhat fainter at higher redshifts. Again, there is no clear trend in the other parameters over this redshift range. The faint-end slope in all three bands is consistent with a value of α ~ 1.3 to 1.4.

Due to the coupling between M* and α in the Schechter function, their evolution with redshift is not independent and a trend in one parameter may be correlated with the other. A better way to characterize the evolution of the LF, as well as the contribution to the total LF from the type-dependent LFs, is to integrate the LF over all magnitudes to derive the average luminosity density. In § 4.2 we investigate this further.

To extend the study of the rest-frame U-, B-, and R-band LFs to z ~ 2, we use the Ks-selected sample. This is important since galaxies start to drop out of the R band–selected surveys at z ~ 1, where this band probes wavelengths shorter than the 4000 Å break. Therefore, using an optically selected sample beyond this redshift only detects galaxies that are very blue. As an example, with our limiting magnitudes R < 24.5 and Ks < 23.2, we are able to detect galaxies with MB ~ 17.4 and MB ~ 16.9 at

### TABLE 3

**Best-fitting Schechter Function Parameters for Rest-Frame B-band Luminosity Functions**

| Redshift Range | M* - 5 log h0 | α | M_0 [10^8 (Mpc/h_0)^3 mag^{-1}] | log ρ_r [ergs s^{-1} Hz^{-1} (h_0 Mpc^3)] | Spectral Types |
|----------------|---------------|----|---------------------------------|--------------------------------|----------------|
| 0.1 < z < 0.5 | -21.22^{+0.10}_{-0.06} | -1.3^{+0.04}_{-0.01} | 28.1^{+2.9}_{-1.2} | 26.73 ± 0.04 ± 0.06 | All |
| 0.5 < z < 0.75 | -18.72^{+0.12}_{-0.08} | -1.02^{+0.08}_{-0.03} | 42.6^{+0.09}_{-0.09} | 26.80 ± 0.03 ± 0.07 | All |
| 0.75 < z < 1.0 | -20.32^{+0.20}_{-0.16} | -1.30^{+0.20}_{-0.17} | 17.7^{+4.4}_{-3.3} | 26.70 ± 0.05 ± 0.07 | All |

Notes.—Data are for a R band–selected sample. Luminosity densities are derived by integrating LFs characterized by the best-fitting Schechter function parameters. First errors represent statistical errors, while second errors represent cosmic variance (see text for details). For early types marked with an asterisk, we have excluded the faint upturn at M_B ~ -17.5.

### TABLE 4

**Best-fitting Schechter Function Parameters for Rest-Frame J-band Luminosity Functions**

| Redshift Range | M* - 5 log h0 | α | M_0 [10^8 (Mpc/h_0)^3 mag^{-1}] | log ρ_r [ergs s^{-1} Hz^{-1} (h_0 Mpc^3)] | Spectral Types |
|----------------|---------------|----|---------------------------------|--------------------------------|----------------|
| 0.1 < z < 0.5 | -23.68^{+0.44}_{-0.34} | -1.48^{+0.06}_{-0.05} | 7.7^{+1.7}_{-0.9} | 27.23 ± 0.06 | All |
| 0.5 < z < 0.75 | -23.19^{+0.52}_{-0.48} | -1.37^{+0.39}_{-0.33} | 12.7^{+3.1}_{-1.9} | 27.42 ± 0.04 | All |
| 0.75 < z < 1.0 | -23.09^{+0.24}_{-0.22} | -1.31^{+0.24}_{-0.22} | 19.7^{+4.9}_{-6.3} | 27.30 ± 0.04 | All |

Notes.—Data are for a Ks band–selected sample. Luminosity densities are derived by integrating LFs characterized by the best-fitting Schechter function parameters. Errors represent statistical errors. For early types marked with an asterisk, we have excluded the faint upturn at M_J ~ -19.0.
z = 0.5 in the two bands, respectively (assuming a Sbc galaxy template). At z = 1.5, we can detect galaxies with $M_B \lesssim -21.9$ and $-19.7$, using the $B$- and $K_s$-selected catalogs, respectively, clearly showing that we reach significantly fainter rest-frame $B$-band magnitudes at high redshift using the $K_s$ selection. It is therefore useful to directly compare the LF derived using exactly the same methods on the $R$- and $K_s$-selected catalogs.

In Figures 8–10, we show the evolution of the rest-frame $U$-, $B$-, and $R$-band LFs in six roughly equal comoving volume redshift bins from $z = 0.1$ to 2. In the lowest redshift bin, we fit $M^*$, $\alpha$, and $\phi^*$, while for the higher redshift bins we adopt the faint-end slope from the lowest redshift bin and fit only $M^*$ and $\phi^*$. The resulting best-fit Schechter functions are shown in the figures as solid lines and are listed in Table 5. For reference, in the five highest redshift bins we show the best-fitting Schechter function derived in the low-redshift bin with dashed lines.

Examining Figure 8 and Table 5, we find that the characteristic magnitude in the $U$ band brightens by $\sim 0.9$ mag from $z = 0.6$ to $\sim 1.9$, which indicates an evolution with redshift similar to that found in the $R$-selected sample. The rest-frame $U$ band LF also shows a strong decline in $\phi^*$ at higher redshift. We see no strong evolution in $M^*$ with redshift in the rest-frame $B$ and $R$ bands, but we note a decline in $\phi^*$ at higher redshift.

We find good agreement between the $R$-selected and $K_s$-selected luminosity functions in the redshift range where they overlap. For example, at $z = 0.64$ ($R$ selected) and $z = 0.62$ ($K_s$ selected), we find $M^*_B = -21.46$ and $-21.43$, as well as $M^*_U = -20.08$ and $-20.28$, for the two different samples, respectively.

In Figure 9 we compare our results with the predictions of a semianalytic model of galaxy formation that has been shown to produce good agreement with the optical luminosity function at redshift zero and the rest-frame $UV$ LF of Lyman break galaxies.
Fig. 7.—Rest-frame $J$-band luminosity function. Symbols are the same as in Fig. 5.

Fig. 8.—Rest-frame $U$-band luminosity function, based on the $K_s$-band–selected catalog. Each redshift bin contains the same comoving volume. The solid line shows the best-fit Schechter function for which the faint-end slope, $\alpha$, has been fixed to the value measured in the lowest redshift bin. The dashed line shows the best-fit Schechter function derived in the low-redshift bin.
Fig. 9.—Rest-frame $B$-band luminosity function (for more information, see Fig. 8). Blue lines show results from a semianalytic model (see text).
Fig. 10.—Rest-frame $R$-band luminosity function (for more information, see Fig. 8).
at $z = 3$ (Somerville & Primack 1999; Somerville et al. 2001, hereafter SPF01). The predictions are based on the collisional starburst model described in SPF01 and computed using the same cosmology used throughout this paper ($\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$).

We find qualitatively good agreement between the observations and the model predictions at all redshifts to the completeness limit in each bin. At magnitudes fainter than we can observe, there is a discrepancy between the models and the extension of the Schechter function fitted in the sense that the model systematically produces more faint galaxies than the Schechter function would imply. This discrepancy increases with redshift and affects the comparison between the observed and predicted evolution of the luminosity density as discussed below. It is not yet clear whether the models overpredict the number of faint galaxies at high redshifts or whether our assumption of a fixed, non-evolving, faint-end slope is incorrect. This demonstrates that probing to fainter magnitudes would provide a strong test of the models. In the discussion in § 5 we compare our results on the LF with results taken from the literature.

### 4.2. Luminosity Density

The luminosity density is calculated by integrating the LF over the luminosity. To correct for incompleteness, we approximate the LF by the estimated Schechter function parameters and integrate this over all luminosities. The luminosity density is then given by

$$\rho_\nu = \int L_\nu \phi(L_\nu, z) dL_\nu = \Gamma(2 + \alpha)\phi^* L_\nu \alpha \Gamma(2 + \alpha)$$

In Figure 11, we show the evolution of the luminosity density with redshift over the $0.1 < z < 1$ range for the rest-frame $U$, $B$ (WFI based), and $J$ bands (ISAAC based). Circles show the evolution when fitting all Schechter parameters in each bin ($M^*$, $\alpha$, and $\phi^*$), while triangles show the evolution assuming

![Figure 11](image-url)

**FIG. 11.—Evolution of the luminosity density as a function of redshift for rest-frame $U$, $B$, and $J$-bands (circles).** The luminosity densities in the two higher redshift bins assuming a fixed faint-end slope are shown with triangles (circles and triangles overlap in the lowest redshift bin). Predictions from a semi-analytical model are shown as dashed lines.
a fixed faint-end slope. The latter are somewhat offset in the x-direction for clarity.

We find that between $z \sim 0.4$ and $0.9$ there is a mild increase in the $U$-band luminosity density by a factor of $\sim 1.3$. In the $B$ and $J$ bands, there is an increase in the luminosity density between the low- and midredshift bins and a slight decrease at higher redshifts. The trend in the $B$- and $J$-band luminosity density is consistent with being roughly constant over this epoch, especially when cosmic variance is considered. We obtain similar results, well within the 1 $\sigma$ errors, whether we leave the faint-end slope free or fix it to the value in the lowest redshift bin.

In Figure 11, we also plot predictions from semianalytical models (SPF01) as dashed lines. The models are in broad agreement with observations predicting a stronger evolution in the $U$ band compared to longer wavelength bands, especially the $J$ band. The observed bump in the luminosity densities in the midredshift bin, which is contrary to the more smooth-model prediction, suggests that there is an overabundance in the $0.5 < z < 0.75$ bin compared to the $0.75 < z < 1.0$ bin due to cosmic variance. An overabundance in this redshift range in the CDFS is also found by the VVDS (Le Fèvre et al. 2005), which suggests that there is a wall-like pattern at $z \sim 0.7$.

In Figure 12, we show the fractional contribution to the luminosity density at $0.1 < z < 1.0$ from galaxies of different spectral types. In the $U$ and $B$ bands, we show this for all three redshift bins, while for the $J$ band we plot only the lowest redshift bin. In the highest redshift bins, the small numbers of galaxies in the $K_s$-selected catalog do not allow us to calculate fractional contributions with sufficient accuracy. Note that the redshift evolution in the fractions should only be marginally affected by cosmic variance, since the total number of galaxies does not enter explicitly here. In the lowest redshift bin, we note that a large part of the luminosity density comes from late-type galaxies in all bands, with the main difference being that the starburst contribution is higher and the early-type contribution is lower in the $U$ band compared to the other bands. In both the $B$ and $J$ bands, about 30% of the light comes from early-type galaxies.

While there is only a weak trend in the evolution of the composite luminosity density in the $U$ and $B$ bands (Fig. 11), there is significant evolution of type-specific luminosity densities, as shown in Figure 12. In the $U$ band, the fraction of the luminosity density contributed by the starburst types increases by a factor of $\sim 2.4$ over the redshift range, while the fractional contribution of both late-type and early-type galaxies decreases with redshift. In absolute terms, the starburst luminosity density increases by a factor of $\sim 3$ over the redshift interval considered. The overall increase in the $U$-band luminosity density is therefore mainly due to the increase in the contribution by the starburst population. The same trends seen in the $U$ band are also present in the $B$ band. However, while the starburst fraction increases, as in the $U$ band (here by a factor of $\sim 2.5$), because the overall fraction of light contributed by starburst types is lower, this does not affect the evolution of the total luminosity density as strongly as in the $U$ band.

In Figure 13, we show a compilation of results from the literature for the rest-frame $B$-band luminosity density for $0 < z < 2$, along with our results based on the $R$-selected and $K_s$-selected catalogs. We show error bars corresponding to the Poisson errors only (black error bars) and error bars including cosmic variance (gray error bars), estimated as described in § 3.2. We find that the luminosity densities derived from the $R$- and $K_s$-selected samples show good agreement in the redshift range where they overlap.

We also find consistency between our results and those from the literature, supporting a mild increase in the $B$-band luminosity between the local value and redshift $z \sim 1$. In the overlapping redshift range ($0.3 < z < 1.2$), there is also a good agreement between our results and COMBO-17 (Wolf et al. 2003). Compared to the local value from Norberg et al. (2002), both this investigation and COMBO-17 find an increase in the rest-frame $B$-band luminosity density by a factor of $\sim 1.7$ between $z \sim 0$ and 0.9. Over the same redshift range, the Lilly et al. (1996) results, when converted to our assumed cosmology, imply a stronger increase (by a factor of $\sim 2.5$), but the difference is within the errors. Note that the original increase reported by Lilly et al. was steeper (up by a factor of $\sim 3.7$ compared to the local value from Norberg et al. 2002) due to their use of a cosmology with $q_0 = 0.5$ and $\Omega_0 = 1$. At high redshifts ($z > 1.2$), we find somewhat lower luminosity densities compared to those of Connolly et al. (1997); however, we are in good agreement with the data point at $z \sim 1.7$ from Dickinson et al. (2003). Note here that both the Connolly et al. and the Dickinson et al. results are based on data from the Hubble Deep Field, but Dickinson et al. include Near Infrared Camera and Multi-Object Spectrometer (NICMOS) NIR data, analogous to the inclusion of ISAAC NIR data in our investigation, so likely resulting in more reliable photometric redshift estimates. Over the redshift range $0.5 < z < 2$, all
the data are consistent with a constant luminosity density in the B band.

Also shown in Figure 13 is a comparison with the semianalytic model predictions. The models predict a continuous decline in the luminosity density from \( z \sim 2 \) to the present. As seen in Figure 9, the models agree well with the observed luminosity functions over the magnitude range directly probed by the observations. This implies that the stronger evolution in the luminosity density predicted by the models is entirely due to a population of galaxies too faint to be directly constrained by our observations. Whether or not this population indeed exists remains to be seen.

5. DISCUSSION AND CONCLUSIONS

5.1. Optical Bands

Using the GOODS data set, including both HST ACS and ground-based photometry from \( U \) through \( K_s \), we have used photometric redshifts to study the evolution of the LF and luminosity density over the redshift range \( 0 \leq z \leq 2 \). We have derived the rest-frame optical (\( U \) and B band) LF in the range \( 0.1 \leq z \leq 1 \) based on an R-selected catalog and used a smaller area but very deep \( K_s \)-selected catalog to derive the rest-frame U-, B-, and R-band LFs to \( z \sim 2 \) and the NIR (\( J \) band) LF to \( z \sim 1 \).

At \( z \leq 1 \), we detect a brightening of the characteristic magnitude with increasing redshift in optical bands based on the R band—selected sample. A brightening in the U band is also found to \( z \sim 2 \), using the \( K_s \)-selected sample, while there is no clear trend in the B or \( z \) band at \( z \leq 0.7 \), based on the latter sample.

In Figure 14 we compare the characteristic magnitude derived from GOODS with results taken from the literature. The GOODS data are shown as circles (\( K_s \) selected) and triangles (\( R \) selected), with blue, green, and red representing the rest-frame \( U \), B, and R bands, respectively. Results from the literature were converted to our adopted cosmology and AB magnitudes when necessary.

In the \( U \) band (Fig. 14, bottom) there is an excellent agreement between our results and the results from the FORS Deep Field (Gabasch et al. 2004; diamonds). There is a clear trend of a brightening of \( M^* \) with redshift. Compared to the “local” value from SDSS (Blanton et al. 2001), we find a brightening of the characteristic magnitude by \( \sim 2.1 \) mag to \( z \sim 1.9 \). This is consistent with recent results from VVDS (Ilbert et al. 2005), which measures a brightening of \( M^*_U \) by \( 1.8-2.4 \) mag between \( z = 0.05 \) and 2.0. In the \( B \) band (Fig. 14, middle) there is also good agreement between GOODS data and the FORS Deep Field, as well as with results from Poli et al. (2003; open squares). The results from COMBO-17 (Wolf et al. 2003; open circles) are consistent with the other results but have higher scatter, and the two highest redshift points are significantly brighter than the other measurements. Note, however, that one reason for the scatter in the Wolf et al. points is the use of a nonfixed faint-end slope when determining \( M^* \) in COMBO-17. The covariance between \( M^* \) and \( z \) causes a higher scatter in \( M^* \) between bins compared to the case in which \( z \) is fixed to a common value in all bins. The brightening of \( M^*_B \) between the local value from SDSS and our measurement at \( z \sim 1.9 \) is \( \sim 0.8 \) mag. This evolution is strongest at \( z \leq 0.7 \). At higher redshifts, our results are consistent with a flat evolution. Finally, in the \( R \) band (Fig. 14, top), the scatter between measurements is the largest. There is no clear trend in either GOODS, COMBO-17, or data from Chen et al. (2003; open triangles) of a brightening of \( M^* \) with redshift. When comparing to the local SDSS measurement, both GOODS and COMBO-17 find brighter characteristic magnitudes. The evolution in the GOODS data is \( \sim 0.7 \) mag to \( z \sim 1.9 \), with the strongest evolution at \( z \leq 0.7 \), similar to that in the other bands.
In summary, the nonlocal measurements show characteristic magnitudes that are brighter than the low-redshift ("local") values taken from SDSS (Blanton et al. 2001; filled stars) and 2dF GRS (Madgwick et al. 2002; open star), with a more significant difference in shorter wavelength bands. The faint-end slope of the LF in all bands is consistent with a value of \( 1.3 \) to \( 1.4 \), and we see no evidence for strong evolution in the faint-end slope to \( z \approx 1 \) in any band.

We find that the shape of the LF is strongly dependent on spectral type, consistent with the results from 2dF GRS (Madgwick et al. 2002) and COMBO-17 (Wolf et al. 2003). In particular, we note that the starburst-type population has a characteristic luminosity that is significantly fainter than the composite LF and that the early-type LF has more of a Gaussian shape, with a possible upturn at faint magnitudes. This upturn in the early-type LF has also been reported by Madgwick et al. (2002) on the basis of the 2dF GRS. We also find significant evolution with redshift in the LF, with the contribution from starburst galaxies to the total luminosity density increasing with redshift. Again, these results are consistent with similar findings based on COMBO-17 reported in Wolf et al. (2003).

The LFs derived from our \( R \)-selected and deep \( K_s \)-selected catalogs agree well out to \( z \approx 1 \), indicating that at \( z \leq 1 \), \( R \)-selected surveys (\( R \leq 24 \)) are not likely to be missing a large population of the objects that would be selected in the \( K \) band at \( K \leq 22 \). This is encouraging for the large upcoming \( R \leq 24 \) selected spectroscopic surveys such as DEEP and VVDS.

Integrating our LF results using equation (8), we obtain estimates of the luminosity density in the rest-frame \( U \), \( B \), and \( R \) bands to \( z \approx 2 \) and in the \( J \) band to \( z \approx 1 \). The \( U \) band shows a rather mild increase (by about a factor of 1.3) between \( z \approx 0.4 \) and \( z \approx 0.9 \), based on the \( R \)-selected sample. At \( z \geq 1 \), we do not detect any clear trend using the \( K_s \)-selected sample. The \( B \) - and \( R \)-band luminosity densities are consistent with being constant to \( z \approx 2 \). This evolution could be significantly underestimated, however, if the faint-end slope at high redshift is actually steeper than we have assumed.

We find that our luminosity function determinations agree fairly well with the predictions of a semianalytic model of galaxy formation.
formation over the magnitude and redshift range probed by the observations. The shape of the predicted luminosity function deviates from a Schechter form, especially at high redshift, producing an excess of both \(L > L_\star\), and \(L < L_\star\) galaxies. These problems are endemic to CDM-based models and are well known. It is clear, though, that the models produce at least as many luminous \((L > L_\star)\) galaxies at high redshift \((1 < z < 2)\) as are implied by our observations, while some previous works have suggested that semi-analytic models may have difficulty in this regard (e.g., Somerville et al. 2004b; Glazebrook et al. 2004). Because of the combined effects of a decrease in the excess of bright galaxies relative to a Schechter fit, a mild decrease in \(L_\star\), and a flattening of the faint end of the LF with time, the models predict a monotonically decreasing luminosity density from \(z \sim 2\) to the present, in contrast with the rather flat luminosity density implied by our observations. However, the models do predict a much flatter dependence of luminosity density on time in the NIR bands than in the optical and UV, as seen in the data, consistent with an overall decrease in the global specific star formation rate (star formation rate per unit stellar mass) over time.

5.2. NIR Bands

In the \(J\) band, we find a trend in which the characteristic magnitude, \(M_\star\), gets fainter over the range \(z \sim 0.4\) to \(\sim 0.9\) by \(\Delta M_\star \sim 0.6\). If we fix the faint-end slope to the value in the lowest redshift bin, the evolution is less significant, \(\Delta M_\star \sim 0.3\). A mild fading of \(M_\star\) is also found by Pozzetti et al. (2003), who measure \(\Delta M_\star \sim 0.14\) between redshifts \(z \sim 0.5\) and \(\sim 1.05\). However, the error bars are larger than this difference, and the results are therefore not significant. An opposite trend is found by Feulner et al. (2003), who find a brightening \(\Delta M_\star \sim -0.6\) between redshifts \(z \sim 0.24\) and \(\sim 0.48\).

In Figure 15, we compare the \(J\)-band LF derived in this paper with the LFs from Pozzetti et al. (2003) and Feulner et al. (2003). We have chosen bins at similar redshifts for this comparison, i.e., \(z = 0.39, 0.50,\) and \(0.88\) for the GOODS, Pozzetti et al. (2003), and Feulner et al. (2003) data, respectively. Inspecting the figure, we find an excellent agreement between the surveys. Despite this, when comparing the Schechter function parameters derived in the different surveys, we find that numbers differ significantly. The characteristic magnitude is \(M_\star = -23.68, -22.93,\) and \(-22.98\) for this investigation, Feulner et al. (2003), and Pozzetti et al. (2003), respectively. The faint-end slope is \(\alpha = -1.48, -1.00,\) and \(-1.22\), and the normalization is \(\phi = 0.0008, 0.0026,\) and \(0.0020 \text{ magn}^{-1} h_{70}^{-3} \text{ Mpc}^{-3}\), respectively, for the three investigations. However, comparing Schechter function parameters one-to-one can be misleading, since there is a coupling between the different parameters. As an alternative, we use equation (8) to derive the luminosity density in the three surveys. We find \(\log \rho = 27.23, 27.23,\) and \(27.20\) ergs s\(^{-1}\) Hz\(^{-1}\)(\(h_{70}\) Mpc\(^{-3}\)) for the three surveys, respectively. This agreement is excellent and further stress that comparisons using only one of the Schechter parameters may be misleading. Figure 15 also illustrates that the combination of depth and wide area in GOODS results in significantly better statistics, especially at the faint end, compared to those of the other investigations. We find a mild increase in the \(J\)-band luminosity density between \(z \sim 0.4\) and \(\sim 0.9\); results, however, are also consistent with being constant.

At longer rest-frame wavelengths, Drory et al. (2003) and Caputi et al. (2004) report a mild brightening of the characteristic magnitude with redshift in the rest-frame \(K\) band, opposite to the trend found here in the \(J\) band. Deriving the redshift evolution in the rest-frame \(K\) band using observed \(K\) band data relies on proper \(K\)-corrections. Local \(K\)-corrections in the NIR are well known; however, any redshift dependence on the \(K\)-corrections affects the results. In addition, a bias in the determination of \(M_\star\) may be introduced if there is a differential trend in the redshift evolution in \(M_\star\); i.e., the brightening gets larger at shorter wavelengths, as reported by Ilbert et al. (2005), who find an evolution in \(M_\star\) that is strongest in the \(U\) band and becomes monotonically weaker at longer rest-frame wavelengths (including the \(B, V, R,\) and \(I\) bands). As the observed \(K\) band probes shorter rest-frame wavelengths at higher redshifts, the differential trend described above could mimic brightening in \(M_\star\) with redshift.

We also note that if we make the simple assumption that the evolution in \(M_\star\) is proportional to wavelength, the results from Ilbert et al. (2005) suggest that we might expect a turnover at approximately the NIR \(J\) band, where \(M_\star\) starts to become fainter with redshift, consistent with what is found here in the \(J\) band. Therefore, further investigations in the rest-frame NIR are needed to firmly establish the evolution of the characteristic luminosity. Observations in the mid-infrared with the Spitzer Space Telescope will here be of great importance.

While the optical light (especially \(U\) band) is related to the underlying star formation, the NIR (e.g., the \(J\) band) light is more directly related to the underlying stellar mass of the galaxies. The opposite trends observed in the optical and NIR for the characteristic magnitude therefore suggest a scenario in which the star formation rate in galaxies increases with redshift, while the underlying stellar mass decreases, or, equivalently, one in which the specific star formation rate (star formation rate divided by stellar mass) decreases with time. These trends are in qualitative agreement with predictions from the hierarchical clustering scenario. In a separate paper, we use the SEDs constructed here to estimate the stellar mass of each galaxy and to directly estimate the rate of stellar mass buildup in our sample over the redshift interval from \(z \sim 2\) to the present (Somerville et al. 2005).

The steep faint-end slope that we obtain in the \(J\) band in our lowest redshift bin \((\alpha = -1.48\pm0.06)\) is consistent with the slope, \(\alpha = -1.22\pm0.22\), derived by Pozzetti et al. (2003). However, the
faint-end slope that we find seems inconsistent with the one derived for nearby galaxies from 2MASS. For example, Kochanek et al. (2001) found $\alpha = -1.09 \pm 0.06$ in the 2MASS $K$ band. We would not expect such a strong dependence on redshift or such a large difference between the $J$ and $K$ bands. However, Kochanek et al. include 2MASS galaxies with $M \leq M^* + 3$ mag when fitting the Schechter parameters, while we reach significantly deeper, $M < M^* + 6$ mag. To investigate, we recalculated our Schechter parameters using a faint cutoff at $M = M^* + 3$ mag. We find $\alpha = -1.15^{+0.21}_{-0.20}$, consistent with the results from 2MASS. The reason for the significant increase in the steepness of the faint-end slope at the faint magnitudes reached in this investigation is that we start to probe the abundant population of faint starburst galaxies. This is evident in Figure 4, which shows that the steep starburst population makes the composite LF turn steep at faint magnitudes. Contrary to this, the shallower 2MASS does not reach this abundant population and therefore finds a flatter faint-end slope. This illustrates how the depth of the survey, together with the covariance between $M^*$ and $\alpha$, can significantly affect the derived Schechter function parameters. Moreover, another investigation based on NIR data that is deeper than 2MASS but shallower than ours also found a steeper faint-end slope (Huang et al. 2003).

We thank the GOODS team, in particular Rafal Idzi and Kyungssoo Lee, for their efforts in data reduction and cataloging. Support for the GOODS HST Treasury program was provided by NASA through grants HST-GO-09425.01-A and HST-GO-09583.01 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NASS-26555. This work is based on observations collected at the European Southern Observatory, Chile (ESO programs 168.A-0485, 170.A-0788, 64.O-0643, 66.A-0572, 68.A-0544, 164.O-0561, 169.A-0725, 267.A-5729 66.A-0451, 68.A-0375 164.O-0561, 267.A-5729, 169.A-0725, and 64.O-0621). M. D. and L. A. M. acknowledge support from the Spitzer Legacy Science Program, provided by NASA through contract 1224666 issued by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract 1407.

APPENDIX

A1. CALCULATING REST-FRAME ABSOLUTE MAGNITUDES

The rest-frame absolute magnitude $M_X$ in a filter $Y$ is calculated using the general formula

$$M_Y = m_X - 5 \log(D_L(z)/10 \text{ pc}) - K_{XY}(z, T),$$  \hspace{1cm} (A1)

where $m_X$ is the observed apparent magnitude in filter $X$, $D_L(z)$ is the luminosity distance, and $K_{XY}(z, T)$ is the $K$-correction. The luminosity distance is given by

$$D_L(z) = \frac{c(1+z)}{H_0|\Omega_k|^{1/2}} \sinh \left\{ |\Omega_k|^{1/2} \int_0^z \frac{[\Omega_m(1+z')^3 + \Omega_k(1+z')^2 + \Omega_L]^{-1/2} dz'}{dz'} \right\},$$  \hspace{1cm} (A2)

where $\Omega_k$ is the curvature term defined as $\Omega_k = 1 - \Omega_m - \Omega_L$ and $\sinh$ is defined as $\sinh$ for $\Omega_k > 0$ and $\sin$ for $\Omega_k < 0$ (Misner et al. 1973). If $\Omega_k = 0$ then $\sinh$ and the $|\Omega_k|^{1/2}$ terms are set equal to 1.

We use the formalism in Kim et al. (1996) and Hogg et al. (2002) to calculate the $K$-correction at redshift $z$ for a galaxy template $T$. The generalized equation for calculating the $K$-correction is

$$K_{XY}(z, T) = -2.5 \log \frac{1}{(1+z)} \int \frac{d\lambda_0}{d\lambda_0} \lambda_0 f_T(\lambda_0) X(\lambda_0) \int d\lambda_c \lambda_c g_T(\lambda_c) Y(\lambda_c)$$ \hspace{1cm} \int d\lambda_c \lambda_c f_T((1+z)\lambda_c) Y(\lambda_c),$$  \hspace{1cm} (A3)

where $\lambda_0$ is the wavelength in the observed frame, $\lambda_c$ is the wavelength in the emitted frame, $X(\lambda)$ and $Y(\lambda)$ are the filter transmission curves (including corrections for the detector quantum efficiency), $f_T$ is the SED of the template $T$, and $g_T$ is the SED of the standard source used to normalize the magnitudes. For AB magnitudes the standard source is a flat (constant) spectrum in frequency space, $g_T(\nu) = $ const. In wavelength space as used here, this corresponds to $g_T(\lambda) = c^{-1} g_T(\nu)$.

If we know the correct redshift and the correct SED representation of the observed galaxy, we can calculate the exact rest-frame absolute magnitude with errors only consisting of the observed photometric errors. However, the true spectral type of the observed galaxy is generally not known. Instead, we represent the galaxy’s SED by the best-fitting template derived from the photometric redshift-fitting procedure. To minimize the dependence on the SED, we use the observed filter that best matches the rest-observed waveband of interest; i.e., we want to use an observed filter $X$ such that

$$\min \{|\hat{\lambda}_X - \hat{\lambda}_Y(1+z)|\},$$  \hspace{1cm} (A4)

where $\hat{\lambda}_X$ and $\hat{\lambda}_Y$ are the effective wavelengths of the observed filter and the observed filter in the rest-frame filter in which we want to calculate the absolute magnitude. In case of a perfect match, the $K$-correction is nearly independent of the assumed SED, while the dependence on the SED increases with the distance between the observed filter and the rest-observed filter.

When calculating absolute magnitudes in this investigation, we use the two observed filters $X_a$ and $X_b$ that satisfy equation (A4) and

$$\hat{\lambda}_X \leq \hat{\lambda}_Y(1+z) < \hat{\lambda}_X.$$  \hspace{1cm} (A5)
From the apparent magnitudes in filters $X_a$ and $X_b$ (i.e., $m_{X_a}$ and $m_{X_b}$), we calculate the corresponding absolute magnitudes $M_{X_a}$ and $M_{X_b}$ using equation (A1). Thereafter, we interpolate to get

$$M_Y = M_{X_a} \left( \lambda_{X_a} - \lambda_Y (1 + z) \right) / (\lambda_{X_a} - \lambda_{X_b}) + M_{X_b} \left( \lambda_Y (1 + z) - \lambda_{X_b} \right) / (\lambda_{X_b} - \lambda_{X_a}).$$  \hspace{1cm} (A6)

In cases for which we do not have two filters available that straddle the desired rest-frame wavelength, we use the nearest observed magnitude according to equation (A4) and thereafter set $M_Y$ to either $M_{X_a}$ or $M_{X_b}$, depending on which is available.

### A2. ERRORS

When calculating the LF using the modified $1/V_{\max}$ method (eq. [5]), the redshift probability distribution for each object corresponds to a distribution in absolute magnitudes representing the uncertainty in the latter. However, for many applications it is desirable to have an explicit measurement of the error in the derived rest-frame absolute magnitude. For completeness, we here give a recipe for how to derive these errors.

Errors in the resulting absolute magnitudes ($\sigma_{\text{tot}}$) mainly come from three sources: (1) photometric errors ($\sigma_m$), (2) errors due to redshift uncertainty ($\sigma_z$), and (3) errors due to uncertainty in the best-fitting template ($\sigma_T$). Here we consider the photometric errors to be known and calculate the remaining two. The magnitude errors due to uncertainty in the redshift are largely dominated by the uncertainty in the luminosity distance. We estimate this error using Monte Carlo (MC) simulations in which we recalculate the luminosity distance after adding random errors to the photometric redshift. The distribution of random errors is assumed to have a $1 \sigma$ dispersion corresponding to the interval containing 68% of the redshift probability distribution.

The error due to uncertainty in spectral type is estimated using MC simulations in which we vary the SED when calculating the $K$-correction in equation (eq. [A1]). In the photometric redshift code, we use a number of SEDs (numbered 1, 2, 3, etc.) for which the templates follow an evolutionary path from early types to late types. In the simulations we assign to each object with a nominal best-fitting template $N$ a new SED with a random type in the range $N - 1/2$ to $N + 1/2$. With this interpolated type we calculate the absolute magnitude and estimate the variations caused by the change in SEDs. The MC simulations are repeated 10,000 times for each object. Finally, to get the total error, we add the three parts in quadrature:

$$\sigma_{\text{tot}}^2 = \sigma_m^2 + \sigma_z^2 + \sigma_T^2.$$  \hspace{1cm} (A7)