THE EVOLUTION OF THE ULTRAVIOLET LUMINOSITY FUNCTION FROM $z \sim 0.75$ TO $z \sim 2.5$ USING HST ERS WFC3/UVIS OBSERVATIONS

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ABSTRACT

We present UV luminosity functions (LFs) at 1500 Å derived from the Hubble Space Telescope Early Release Science WFC3/UVIS data acquired over $\sim 50$ arcmin$^2$ of the GOODS-South field. The LFs are determined over the entire redshift range $z = 0.75$ to 2.5 using two methods, similar to those used at higher redshifts for Lyman break galaxies (LBGs): (1) 13 band UV+optical+NIR photometric redshifts to study galaxies in the range $z = 0.5$ to 2 in three bins of $dz = 0.5$ and (2) dropout samples in three redshift windows centered at $z \sim 1.5$, $z \sim 1.9$, and $z \sim 2.5$. The characteristic luminosity dims by 1.5 mag from $z = 2.5$ to $z = 0.75$, consistent with earlier work. However, the Schechter function parameters, the faint-end slope and the number density, are found to be remarkably constant over the range $z = 0.75$ to 2.5. Using these LF determinations, we find the UV luminosity density to increase by $\sim 1.4$ dex according to $(1 + z)^{-2.3\pm 0.5}$ from $z \sim 0$ to its peak at $z \sim 2.5$. Strikingly, the inferred faint-end slopes for our LFs are all steeper than $\alpha = -1.5$, in agreement with higher-redshift LBG studies. Since the faint-end slope in the local universe is found to be much flatter with $\alpha \approx -1.2$, this poses the question as to when and how the expected flattening occurs. Despite relatively large uncertainties, our data suggest $\alpha \approx -1.7$ at least down to $z \sim 1$. These new results from such a shallow early data set demonstrate very clearly the remarkable potential of WFC3/UVIS for the thorough characterization of galaxy evolution over the full redshift range $z \approx 0.5$ to $z \sim 3$.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: luminosity function, mass function

1. INTRODUCTION

The UV luminosity function (LF) of galaxies is a key diagnostic for establishing the contributions of galaxies of different luminosities and masses to the cosmic star formation rate (SFR) density. In addition, in combination with other measures, like the galaxy mass function, it also provides essential clues as to the causes for the slow down in star formation of galaxies in more recent times since $z \sim 2$.

The UV LF has been studied very extensively at redshifts $2 \leq z \leq 6$, but at lower redshifts ($z \leq 2$), similar deep, high resolution data have not been available. To date the $z < 2$ UV LF has been measured from Galaxy Evolution Explorer (GALEX) data using the dropout technique (e.g., Burgarella et al. 2006; Ly et al. 2009; Haberzettl et al. 2009), and also using spectroscopic or photometric redshifts (e.g., Arnouts et al. 2005; Wyder et al. 2005; Budavári et al. 2005). The main limitations of the GALEX results are (1) the very wide point-spread function (PSF, $\sim 5''$ FWHM), which may cause blending of the UV light from several sources and makes the identification of optical counterparts relatively difficult, and (2) the limited depth ($\sim 25$ mag).

With the installation of the Wide-Field Camera 3 (WFC3) on the Hubble Space Telescope (HST), the efficient coverage of the electromagnetic spectrum at high spatial resolution ($\leq 0.15''$) has been extended to the UV and to the IR. The new IR capability allowed us (and other groups) to perform the first robust measurements of the UV LF at $z \approx 7$–8 in the first epoch data of the HUDF09 (e.g., Oesch et al. 2010b; Bouwens et al. 2010; McLure et al. 2010; Bunker et al. 2010).

The high sensitivity UV imaging capability provided by the WFC3/UVIS channel similarly allows us to derive the UV LF at redshifts below $z \sim 2.5$, where the $\sim 1500$ Å UV flux from galaxies could not be probed efficiently with previous high resolution cameras. While the depth of the current ERS WFC3/UVIS UV data (Windhorst et al. 2010) is less than that of the WFC3/IR data, the present depths still significantly exceed that from any previous UV data set.

We use two different methods for our LF determinations: (1) 13-band UV+optical+NIR photometric redshifts to study galaxies in the range $z \sim 0.5$ to 2 (2) the UV-dropout technique, applied to the UVIS filter set, which allows for the selection of star-forming galaxies at $z \sim 1.3$ to $z \sim 2.8$. The latter dropout samples are similar to the recent selections of Hathi et al. (2010).

In Section 2, we describe the data, the photometric redshift estimates, and the dropout selection. This is followed in Section 3 by our constraints on the UV LF between $z = 0.5$ and $z = 2.8$, and we end with a short discussion on the evolution of the UV LF parameters and luminosity density in Section 4.
Throughout this Letter, we adopt $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, i.e., $h = 0.7$. Magnitudes are given in the AB system (Oke & Gunn 1983).

2. DATA AND SAMPLE SELECTION

2.1. ERS Data Set

The Early Release Science (ERS) UV data cover a total of $\sim$50 arcmin$^2$ of the GOODS-South fields (Giavalisco et al. 2004) in 4 x 2 pointings of WFC3/UVIS in three filters ($UV_{225} - F225W, UV_{275} - F275W, U_{336} - F336W$). Each pointing was covered with five orbits, equivalent to 2778 s, 5688 s, and 5688 s integrations in $UV_{225}, UV_{275}$, and $U_{336}$, respectively. The observations in each band were split into three ($U_{336}$) or four ($UV_{225,275}$) exposures to facilitate cosmic-ray (and bad pixel) removal (see Windhorst et al. 2010 for more information on the data). The rms maps were scaled to the proper noise level, as measured in circular apertures appropriate for the galaxies under study. Using circular apertures of 0.2′′, the measured $\sigma$ point source sensitivities in all three filters are 26.8–26.9 mag.

After masking areas with bad sampling and large residuals from cosmic-ray hits, the final area used in this study with point source sensitivities in all three filters are 26.8–26.9 mag.

Lastly, our catalog was matched against the public GOODS catalogs and candidate stars flagged. At $z_{5850} < 25.5$, this identification is based upon their size (half-light radii <0.09′′) and the SExtractor stellarity parameter (>0.8). Faintward of 25.5, the latter parameter is no longer reliable, and therefore flagging sources with half-light radii <0.09′′ was done if the $V - i$ versus $i - z$ colors of sources were consistent with the stellar sequence (within 0.15 mag). From a visual inspection of the sample of galaxies entering in the LF estimates this has proven to be a very efficient and complete procedure to identify stars.

2.2. Photometric Redshift Selections

In order to derive accurate photometric redshifts, we supplement the high resolution ACS and WFC3/UVIS data with ground-based IR and with Spitzer data, using the GOODS-MUSIC catalog (v2) of Santini et al. (2009). In particular, the GOODS-MUSIC photometry used here is VIMOS $U$, ACS $B_{435}/V_{606}/I_{775}/z_{5850}$, ISAAC $J, H, K$, and Spitzer IRAC 3.6 and 4.5. The GOODS-MUSIC catalog is 90% complete down to $z_{5850} \leq 26$ mag. Matching this catalog to our $B$-selected sources, we find 4165 matches (using a 0.2′′ error tolerance). The UVIS isophotal fluxes are scaled to total fluxes using the ratio of $B$-Band ISO flux to $B$-Band AUTO flux.

Thus, our basic photometry catalog for photo-$z$ estimates consists of seven filter HST data, complemented with four PSF-matched ground-based filters, and the two shortest wavelength IRAC bands. The IRAC 5.8 and 8.0 bands were omitted, since they are dominated by dust and polycyclic aromatic hydrocarbon emission for lower redshift galaxies. Even if galaxies are generally red in $B - z$, we limit our analysis to $B_{336} < 26$ mag to avoid incompleteness corrections due to the $z_{5850}$-band limit. We did not use the WFC3/IR photometry, since it is not available for all sources to keep our analysis as uniform as possible (and our tests show that our selections do not change significantly when these data are included).

Photometric redshifts were estimated from spectral energy distribution (SED) fitting with ZEBRA (Feldmann et al. 2006). The adopted SED set is based on Bruzual & Charlot (2003) composite stellar populations. In particular, we computed 15 median templates as a function of rest-frame $u-J$ color for galaxies in the zCOSMOS survey (Lilly et al. 2007, 2009). Subsequently, these templates were corrected for systematic offsets with respect to the COSMOS photometry (Capak et al. 2007) using ZEBRA, and the major emission lines (Ly$\alpha$, H$\alpha$, H$\beta$, O ii, and O iii) were added using the Kennicutt (1998) relations between UV luminosity and emission line strengths. Finally, dust was added to this set of templates using the Calzetti et al. (2000) dust law with $E(B-V) = 0-0.5$, resulting in a final set of 2052 templates.

We used this template set to derive photometric redshifts for our combined catalog of UVIS and GOODS-MUSIC photometry. We compared our estimates with spectroscopic redshift measurements compiled in the GOODS-MUSIC catalog. From a total of 462 sources with reliable spectroscopy (363 at $z < 1.5$), we find an accuracy of $\sigma_z = 0.037 \times (1 + z)$, with only 6.4% of sources having redshift errors larger than $|\Delta z| > 0.15 \times (1 + z)$. Our photometric redshift estimates are therefore sufficiently precise to derive LFs in bins of $dz = 0.5$.

2.3. UV-dropout Selection

Most of the UV LFs at $z > 3$ are based on an Lyman break galaxy (LBG) selection (e.g., Steidel et al. 1995). The same technique can also be applied to the WFC3/UVIS filters, allowing the selection of star-forming galaxies as UV-dropouts. At $z < 3$, the Lyman break seen in galaxies is primarily the result of neutral hydrogen within the sources themselves, in significant contrast to the situation at $z > 3$, where the break is also due to Lyman-series absorption from the intergalactic medium (IGM).

Our selection criteria are based on standard color–color diagrams, which are shown in Figure 1. In particular, the selection regions are chosen to identify an unbiased sample of star-forming galaxies with dust extinction less than $E(B-V) \sim 0.3$–0.4 guarding against lower redshift interlopers.

Specifically, the adopted selection criteria for $UV_{225}$-dropouts are

$$UV_{225} - UV_{275} > 0.75 \land$$

$$UV_{225} - UV_{275} > 1.67(UV_{275} - U_{336}) - 0.42 \land$$

$$-0.5 < (UV_{275} - U_{336}) < 1.4 \land$$

$$S/N(UV_{275}) > 5.$$

This selects galaxies between $z \sim 1.3$ and 1.7, and results in 72 candidates down to $U_{336} = 26.5$. 

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9 http://archive.stsci.edu/pub/hlsp/goods/v2/
Similarly, for $UV_{275}$-dropouts, the selection criteria are

$$UV_{275} - U_{336} > 1 \land$$

$$UV_{275} - U_{336} > 2.2(U_{336} - B_{435}) - 0.42 \land$$

$$-0.5 < (U_{336} - B_{435}) < 1.1 \land$$

$$S/N(U_{336}) > 5 \land S/N(UV_{225}) < 2$$

selecting galaxies between $z \sim 1.7$ and 2.1, with 131 candidates down to $B_{435} = 26.5$.

And finally, $U_{336}$-dropouts are selected with

$$U_{336} - B_{435} > 1 \land$$

$$U_{336} - B_{435} > 2(B_{435} - V_{606}) \land$$

$$-0.5 < (B_{435} - V_{606}) < 1 \land$$

$$S/N(B_{435}) > 5 \land S/N(UV_{225}/275) < 2$$

returning 434 sources down to $V_{606} = 26.5$ with expected redshifts in the range $z \sim 2.2-2.8$. When applying these criteria, all fluxes below their $1 \sigma$ limits (in the dropout band) are replaced with the respective $1 \sigma$ upper limits.

For the $U_{336}$-dropouts, the stellar sequence runs exactly through the selection window (see Figure 1). However, stars are removed prior to candidate selection using the same identification scheme as for the photo-$z$ sample, resulting in a total of 40 excluded stars. From a final visual inspection of all sources no additional stars were found. A small number of clear diffraction spikes and spurious detections on the wings of large low-redshift galaxies were removed by hand.

Using our photometric redshifts, we estimate the low-redshift interloper fraction of these $UV$-dropout samples to be very small. In particular, only 7% of the sources in the $U_{336}$-dropout sample have $z_{\text{phot}} < 1.75$. Similarly, only 4% and 8% of the sources in our $UV_{275}$- and $UV_{225}$-dropout samples are interlopers, i.e., have $z_{\text{phot}} < 1.25$ and $z_{\text{phot}} < 1$, respectively. Only sources down to the limiting magnitudes of our UV LFs are considered in this estimate (see Section 3.2).

3. RESULTS

3.1. Photometric Redshift LF Results

The UV LFs at 1500 Å in the range $z \sim 0.5-2$ are measured in three bins of photometric redshift of width $dz = 0.5$. The absolute magnitudes are computed from the $UV_{275}$, $U_{336}$ and $B_{435}$ photometry for sources in the redshift range $z = 0.5-1$, $z = 1-1.5$, and $z = 1.5-2$, respectively. $K$-corrections are derived from the appropriate best-fit templates. The UV LFs of galaxies are estimated using the standard $V_{\text{max}}$ estimator (Schmidt 1968) such that

$$\phi(M,dM) = \sum_i \frac{1}{C(m_i)V_{\text{max},i}},$$

where the sum runs over all galaxies in the given redshift and absolute magnitude bin. We only include galaxies with $>5 \sigma$ detections in the corresponding filter, which results in the need for a completeness correction factor $C$. Following Oesch et al. (2007, 2010b), this is determined from Monte Carlo simulations in which we add artificial galaxies to the images and detect them with the same SExtractor parameters as used for the original B-band catalog. The completeness is $>97\%$ to $\leq 25$ mag in the UVIS filters, after which it drops to 50% at 25.8 mag, which is our faint-end limit.

Figure 2 shows the resulting LFs. The best-fit Schechter parameters (Schechter 1976) are tabulated in Table 1. While we sample the faint end rather well, with data that reach $\sim 2$ mag fainter than $M_*$, the relatively small area covered by the ERS data results in some uncertainty on the cutoff at bright magnitudes. Nevertheless, our results are in good agreement with the LFs determined from GALEX byArnouts et al. (2005) and effectively validate those results in data with $\sim 50$ times higher spatial resolution.

3.2. Dropout LF Results

The UV LF of the UVIS dropout sample is computed using standard techniques adopted in LBG studies. In particular, the step-wise LFs are derived using

$$\phi(M[m_i, z_i])dM = N_i/V_{\text{eff}}(m_i),$$
where \( N_i \) are the number of galaxies observed in the magnitude bin \( i \), and the effective volume is given by

\[
V_{\text{eff}}(m_i) = \int_{0}^{\infty} S(m_i, z) C(m_i) \frac{dV}{dz} \, dz.
\]

The selection efficiency \( S \) and completeness \( C \) are again estimated from simulations of artificial galaxies inserted into the observed images. The inserted galaxies are chosen to have a log-normal size distribution, using an extrapolation of the higher-redshift LBG size scaling of \((1 + z)^{-1}\) (Oesch et al. 2010; Bouwens et al. 2004; Ferguson et al. 2004). The colors are set according to the \( z \sim 2.5 \) UV continuum slopes derived in Bouwens et al. (2009, see also Reddy et al. 2008), with additional IGM absorption according to Madau (1995).

Due to the lower sensitivity of the UV data with respect to the optical, red colors across the continuum breaks cannot be accurately measured for galaxies fainter than \( B \sim 26 \). Therefore, only sources with \( V < 26.3, B < 25.5 \), and \( U_{336} < 25.4 \) are used to compute the LFs, ensuring that the selection efficiency is still larger than 50% for \( U_{336}-, UV_{275}-, \) and \( UV_{225}-\)dropout results, respectively. This results in 403, 99, and 60 sources in the three different dropout samples.

The UV LFs for the UVIS dropouts are shown in the right panels of Figure 2. Again, a significant increase at the bright end of the UV LF is seen from lower to higher redshift. Due to the modest size of the present \( UV_{225}- \) and \( UV_{275}-\)dropout samples, the Schechter parameters we derive at \( z \sim 1.5 \) and \( z \sim 1.9 \) are still somewhat uncertain (see Table 1). The \( z \sim 2.5 \) \( U_{336}-\)dropout LF, by contrast, is much better constrained from
our data, extending \( \sim 2 \) mag fainter than \( M_\alpha \) and with a faint-end slope \( \alpha \) established to within \( \pm 0.11 \). Our \( z \sim 2.5 \) LF is in excellent agreement with the \( z \sim 2.3 \) UV LF of Reddy & Steidel (2009).

Note that due to the limited area of the present survey, our results are dominated by cosmic variance, which we estimate to be about 16\%–20\% (Trenti & Stiavelli 2008).

![Figure 3](image-url)  
**Figure 3.** Top three panels: the redshift evolution of UV (\( \lambda \sim 1500–1700 \) Å) LF parameters \( \phi^* \), \( M^* \), and \( \alpha \) over the redshift range \( z \sim 0–8 \). The present determinations are shown with large filled circles. Of particular note, the uncertainties on the Schechter function parameters are frequently much smaller at \( z > 3 \) than at lower redshifts. This is a direct consequence of having very deep \textit{HST} optical surveys. WFC3/UVIS should enable similarly deep future observations in the UV at \( z < 3 \). Also shown are some notable determinations from the literature (Arnouts et al. 2005; Reddy & Steidel 2009; Bouwens et al. 2007, 2008, 2010; Oesch et al. 2007, 2010b; Sawicki & Thompson 2006; Yoshida et al. 2006; Iwata et al. 2007; McLure et al. 2009; Ouchi et al. 2009). Despite some scatter, most faint-end slope determinations at \( z > 0.5 \) are very steep, i.e., \( \alpha \sim -1.7 \). Bottom: the 68\% error contours on \( M^* \) and \( \alpha \) over the redshift range \( z \sim 0.75–2.5. \) The contour at \( z \sim 2.5 \) is from our \( U_{02468} \) dropout sample, the remaining ones are derived from the photometric redshifts. The lower redshift dropout samples result in considerably larger errors and are omitted for clarity.

![Figure 4](image-url)  
**Figure 4.** Redshift evolution of the UV (\( \lambda \sim 1500 \) Å) luminosity density. In the upper panel, the LFs are integrated down to a fixed luminosity of 0.1 \( L^*_z=3 \) (\( L^* \) as derived at \( z = 3 \) by Steidel et al. 1999), while the lower panel shows the total luminosity density. The dark and light blue points are derived from our photo-\( z \) and the dropout samples, respectively. The gray points are based on the literature values shown in Figure 3. The dashed curves are fits to the data at \( z < 2.5 \) and \( z > 2.5 \) of the form \( \rho_L \propto (1+z)^{\beta_L} \). Error bars are computed from Monte Carlo simulations, not accounting for the covariance between the Schechter parameters. They are thus expected to overestimate the real errors. Note, however, that \( \alpha \) was constrained to \( \alpha > -2 \) in order to keep \( \rho_L^{\beta_L} \) finite. This only significantly affected five data points, which are marked with black circles.

### 4. DISCUSSION

The evolution of the Schechter parameters of recent UV LFs in the redshift range \( z \sim 0–8 \) is shown in Figure 3. Our results cover the whole 4.3 Gyr period from \( z \sim 0.75 \) to \( z \sim 2.5 \). Interestingly, in the region of overlap, the LFs we derive from our photometric redshifts and UV-dropout selections are in very good agreement. This suggests that our UV-dropout samples are well defined and reasonably complete.

In Figure 3, our results are compared to several Schechter function estimates from the literature. Within the uncertainties, \( \phi^* \) is found to be fairly constant over the entire redshift range, although there is a weak trend toward higher \( \phi^* \) at lower redshifts.

The most noteworthy trend is the monotonic fading of the characteristic luminosity by a factor of \( \sim 16 \) from \( z \sim 3 \) (\( M^* \) fades from \( -21 \) at \( z \sim 3 \) to \( -18 \) at \( z \sim 0 \)). At \( z > 4 \), \( M^* \) turns over and decreases monotonically again toward higher redshift, such that \( M^*(z = 8) \) is essentially equal to \( M^*(z \sim 1) \).

It is very interesting that all our faint-end slope measurements are steeper than \( \alpha \sim -1.5 \), even at \( z \sim 0.5–1 \), in agreement with the earlier measurements of Arnouts et al. (2005). Despite relatively large error bars, the faint-end slope \( \alpha \) is clearly seen to transition from \( \alpha < -1.5 \) at \( z \gtrsim 0.5–2 \) to a flatter \( \alpha = -1.2 \) in the local universe (but see Treyer et al. 1998, who find a steeper slope locally). With the present data, we cannot determine whether this transition occurs relatively abruptly at low redshift, or smoothly from \( z \sim 2 \) to \( z \sim 0 \).

Finally, in Figure 4 we show the cosmic 1500 Å luminosity density \( \rho_L \) (uncorrected for dust extinction) estimated from the Schechter function parameters. The luminosity density is
shown integrated to \( L > 0.1 L^*_{\text{K3}} \) and also integrated to zero luminosity. Clearly, the evolution of \( \rho_L \) is mainly driven by \( M_\bullet \). From the peak at \( z \sim 2.5 \), the total UV luminosity drops by 1.5 dex to \( z \sim 0 \). This decrease is well described by \( \rho_L(z) \propto (1 + z)^{\beta_L} \), for which we find \( \beta_L(z < 2.5) = 2.58 \pm 0.15 \), in good agreement with earlier measurements (e.g., Schiminovich et al. 2005; Tresse et al. 2007). The evolution at higher redshift follows \( \beta_L(z > 2.5) = -1.82 \pm 0.37 \), \( z \sim 2.5 \) thus marks the high point in the production of the cosmic UV luminosity and is clearly an important epoch for exploring the properties of galaxies (e.g., see Cameron et al. 2010 for a new technique for selecting galaxies in this range with simple color criteria).

The remarkable potential of the HST WFC3/UVIS camera is clear from these new results. This ERS data set with its initial rather shallow observations has demonstrated already that WFC3/UVIS is a powerful tool for exploring galaxy evolution over the redshift range \( z \sim 0.5 \) to \( z \sim 3 \). Deeper data will provide key insights into the decline of the cosmic SFRD since \( z \sim 2 \), particularly at the lowest luminosities. For example, a steep LF with \( \alpha \sim -1.7 \) suggests that star formation efficiencies and feedback processes are only weakly dependent on halo mass (e.g., Trenti et al. 2010).

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