

THE GALEX VIMOS-VLT DEEP SURVEY¹ MEASUREMENT OF THE EVOLUTION OF THE 1500 Å LUMINOSITY FUNCTION

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ABSTRACT

We present the first measurement of the galaxy luminosity function (LF) at 1500 Å in the range $0.2 \leq z \leq 1.2$ based on *Galaxy Evolution Explorer* VIMOS-VLT Deep Survey observations (~ 1000 spectroscopic redshifts for galaxies with $\text{NUV} \leq 24.5$) and at higher z using existing data sets. Our main results are summarized as follows: (1) Luminosity evolution is observed with $\Delta M_* \sim -2.0$ mag between $z = 0$ and $z = 1$ and $\Delta M_* \sim -1.0$ mag between $z = 1$ and $z = 3$. This confirms that the star formation activity was significantly higher in the past. (2) The LF slopes vary in the range $-1.2 \geq \alpha \geq -1.65$, with a marginally significant hint of increase at higher z . (3) We split the sample in three rest-frame ($B - I$) intervals, providing an approximate spectral type classification: Sb–Sd, Sd–Irr, and unobscured starbursts. We find that the bluest class evolves less strongly in luminosity than the two other classes. On the other hand, their number density increases sharply with z ($\sim 15\%$ in the local universe to $\sim 55\%$ at $z \sim 1$), while that of the reddest classes decreases.

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

1. INTRODUCTION

Evidence collected over the past decade suggests that the cosmic, volume-averaged star formation rate (SFR) density has increased from the present to $z \sim 1$ (Lilly et al. 1996; Wilson et al. 2002) with a possible flattening at higher redshift (Steidel et al. 1999; Giavalisco et al. 2004). The details of the evolution in the range $0 \leq z \leq 1$ are still being debated and appear to depend on the selected wavelength. Rest-frame far-ultraviolet (FUV; 1500 Å) observations can provide a sensitive measurement of the ongoing SFR but up to now have only been obtained in the local universe (2000 Å; Sullivan et al. 2000) and at $z \geq 2.5$ (1700 Å; Steidel et al. 1999). The *Galaxy Evolution Explorer* (GALEX) mission now allows us to refine the local FUV measurements (Wyder et al. 2005; Treyer et al. 2005;

Budavari et al. 2005) and to fill the redshift gap where most of the SFR evolution has taken place.

In this Letter, we use a unique spectroscopic sample of ~ 1000 near-ultraviolet (NUV)–selected galaxies to derive the first measurement of the 1500 Å luminosity function (LF) in the range $0.2 \leq z \leq 1.2$. We also use Hubble Deep Field (HDF) data to extend our analysis to $z = 3$. These results allow us to address the evolution of the luminosity density and SFR, presented in a companion paper (Schiminovich et al. 2005). Throughout the Letter, we assume a flat Λ CDM cosmology with $\Omega_M = 0.3$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. DATA DESCRIPTION

We use the data collected in the 2 hr field (02^h26^m00^s, –04°30′00″) by GALEX and by the VIMOS-VLT Deep Survey

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(VVDS). The 2 hr field was observed as part of the *GALEX* Deep Imaging Survey, with a total integration time of $t_{\text{exp}} = 52,763$ s in two channels (FUV ~ 1530 Å and NUV ~ 2310 Å). We restrict the analysis to the central 1° diameter region of the *GALEX* field of view, which provides higher uniformity (Morrissey et al. 2005). The typical point-spread function (PSF) has an FWHM $\sim 5''$. Because of the high source density in these images, the *GALEX* data pipeline (implementing a modified version of SExtractor; Bertin & Arnouts 1996) was run with deblending parameters configured to improve extraction of unresolved point sources at the faint limit. The number counts are $\sim 80\%$ complete at 24.5 (AB system) in the FUV and NUV bands (Xu et al. 2005). Magnitudes were corrected for Galactic extinction using the Schlegel et al. (1998) reddening map and the Cardelli et al. (1989) extinction law with $A_{\text{FUV}}/E(B - V) = 8.29$, $A_{\text{NUV}}/E(B - V) = 8.61$.

The VVDS is a spectroscopic survey with multicolor photometry (Le Fèvre et al. 2003). Deep *BVRI* imaging over 1.2 deg^2 was carried out using the Canada-France-Hawaii telescope, with typical depths of 27, 26, 26.2, and 25.3, respectively, and a PSF better than $1''$ (McCracken et al. 2003). The ongoing deep spectroscopic survey covers $\sim 1950 \text{ arcmin}^2$ with a preliminary sample of ~ 7200 spectroscopic redshifts of galaxies with $17.5 \leq I_{\text{AB}} \leq 24$.

In the UV sample, all sources have at least one optical counterpart (OC) within a radius of $4''$. With the VVDS spectroscopic sample, we match 1157 galaxies with $\text{NUV} \leq 24.5$ and find that 48% are isolated (one OC in $4''$), 36% have two OCs, and 16% have more than two OCs. These fractions are almost constant with magnitude in the range $21.5 \leq \text{NUV} \leq 24.5$ and with redshift. As a preliminary matching procedure, we associate the closest OC to each UV source. This also selects the brightest *B*-band counterpart in 95% of the double-counterpart cases and 85% of the more than two counterpart cases. In the case of NUV sources with several OCs, the UV flux may result from the UV contribution of several sources. Although we do not correct for the UV flux attributed to the chosen OC, we use simulations to estimate the magnitude of the bias.

To test the impact of blends, we divide the NUV flux among the potential OCs determined using a match reliability statistic based on the likelihood estimator of Sutherland & Saunders (1992). We find that the average UV flux overestimate is ~ -0.25 mag in the case of two OCs and up to ~ -0.5 mag for the more complex cases. By comparing the LFs derived for this blend-corrected NUV-selected sample and the original sample, we find that the variations of M_* are less than -0.25 , within the error bars quoted below. This method may be more accurate but still requires several strong assumptions (optical and UV sources are intrinsically unresolved, optical-UV color is fixed). As we have shown that the results are not significantly affected by the adopted method, we use the simplest approach.

Figure 1 shows the $(\text{NUV} - I)$ versus NUV color-magnitude diagram. Isolated objects are displayed with filled circles and multiple counterpart cases with crosses. The spectroscopic sources (red symbols) randomly sample the full range of colors observed in the total sample and are therefore unbiased. For *I*-band saturated galaxies ($\sim 4\%$ with $I_{\text{AB}} \leq 17.5$; green symbols), we estimate that $\sim 95\%$ are at $z \leq 0.2$ using photometric redshifts in *GALEX*–Sloan Digital Sky Survey (SDSS) fields (Budavari et al. 2005). No redshifts were measured for galaxies with $I_{\text{AB}} \geq 24$, selecting against very blue objects, but the small fraction ($\sim 4\%$) is unlikely to affect our results.

Although our preliminary catalog contains galaxies with spectroscopic redshifts between $0 \leq z \leq 1.5$, we restrict the

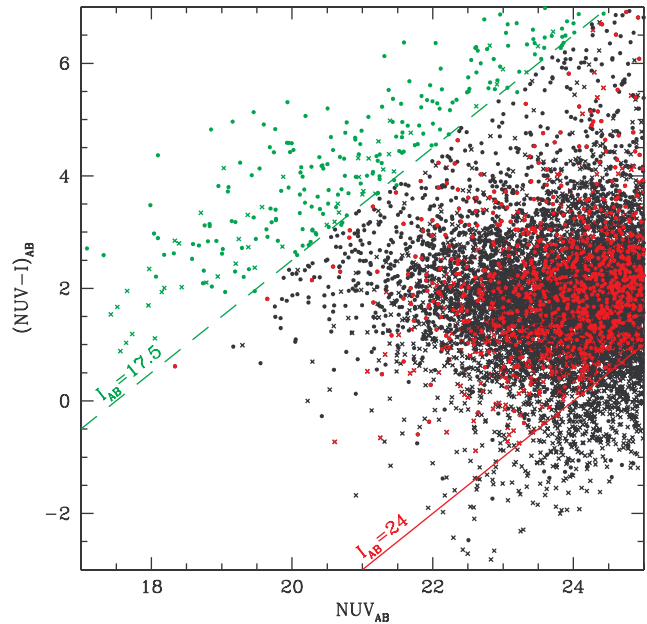


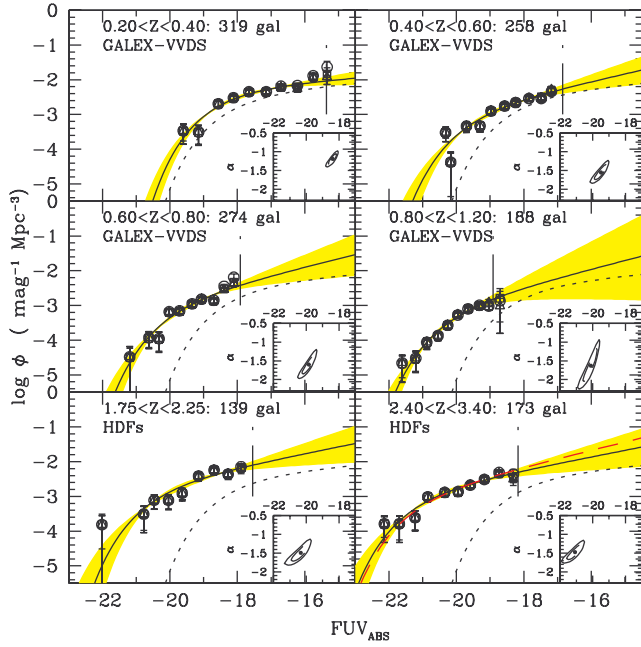
FIG. 1.—Color-magnitude diagram $[(\text{NUV} - I)_{\text{AB}} \text{ vs. } \text{NUV}_{\text{AB}}]$.

sample to the 1039 galaxies in the redshift range $0.2 \leq z \leq 1.2$. The low-redshift cut avoids local galaxies saturated in the *I* band. The high-redshift limit ensures that the 912 Å break falls below the blue edge of the NUV passband.

3. FUV (1500 Å) LUMINOSITY FUNCTIONS

We derived rest-frame FUV absolute magnitudes using *k*-corrected NUV fluxes (with *k*-correction based on spectral energy distribution [SED] fits). This choice yields minimal *k*-corrections, because the average wavelength of the NUV passband samples the rest-FUV interval $1925 \text{ Å} \leq \lambda_{\text{rest}} \leq 1050 \text{ Å}$ over our adopted redshift range. To measure the LF, we use the VVDS LF tool (ALF) by Ilbert et al. (2004b), which includes the $1/V_{\text{max}}$, the C_+ , the stepwise maximum likelihood (SWML), and the Sandage-Tammann-Yahil (STY) estimators. A weight is assigned to each spectroscopic galaxy to take into account the spectroscopic strategy of the VVDS observations and the completeness correction of the NUV number counts. We refer to a forthcoming paper for a complete description of the absolute magnitude and weight measurements.

Figure 2 shows the *GALEX*–VVDS LFs in four redshift bins (*four top panels*) for the four estimators (V_{max} : circles; SWML: triangles; C_+ : squares; STY: solid line). For the STY fits, we show the extrema (shaded area) based on the individual 1σ uncertainty in α and M_* (the likelihood probability contours are shown as insets for $2\Delta \ln \mathcal{L} = 1$ [dashed lines] and for $2\Delta \ln \mathcal{L} = 2.3$ [solid lines]). The vertical lines show the limits beyond which the global sample becomes biased against certain spectral types (see Ilbert et al. 2004a). These values are listed in Table 1 as M_{bias} . Points beyond these limits are not included in the fitting procedures. In general, NUV selection serves to reduce this bias significantly. Finally, we measure the FUV LF at high z using photometric redshifts in the HDF-North and HDF-South (Arnouts et al. 2002; *bottom panels*). For the purpose of rest-frame FUV selection, we define one sample in the range $1.75 \leq z \leq 2.25$ using the F450 passband with $F450_{\text{AB}} \leq 27$ and one sample in the range $2.40 \leq z \leq 3.40$ using the F606 passband with $F606_{\text{AB}} \leq 27$. At $z \sim 3$, we also com-

FIG. 2.—The 1500 Å LF in the range $0.2 \leq z \leq 3.5$.

pare our results with the LF at 1700 Å (Steidel et al. 1999; *red dashed line*). As a reference, we show the local 1500 Å LF derived from GALEX data (Wyder et al. 2005; *dotted lines*). All of the STY parameters are listed in Table 1, and Figure 3 shows the slope (α ; *top panel*) and the M_* (*bottom panel*) parameters versus redshift (GALEX-VVDS sample: *filled circles*; HDF sample: *stars*; Lyman break galaxy [LBG] sample: *open squares*; local sample: *filled squares*).

The faint end slopes vary in the range $-1.65 \geq \alpha \geq -1.2$ for $0.2 \leq z \leq 3$ with a marginal steepening with z (within the 1σ error bars). The M_* versus z plot reveals strong redshift evolution. A significant brightening of order $\Delta M_* \sim -2$ occurs

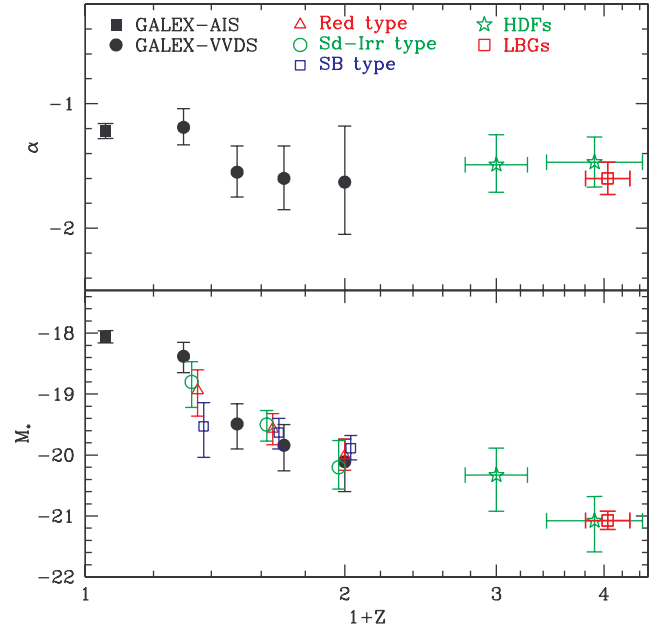


FIG. 3.—Evolution of the LF STY parameters vs. redshift.

in the range $0 \leq z \leq 1.2$. The higher z samples show that the trend continues to $z \sim 3$ at a lower rate ($\Delta M_* \sim -1$). This increase is highly significant with respect to our error bars and the source blending issue discussed in § 2. The brightening of M_* and the steepening of the slope observed at 1500 Å is qualitatively consistent with the evolution detected at longer wavelengths (2800 Å; U and B bands) by Wolf et al. (2003) and Ilbert et al. (2004b).

4. DEPENDENCE OF THE FUV LUMINOSITY FUNCTION ON COLOR

The LF of galaxies has been shown to vary as a function of rest-frame color or spectral type (Blanton et al. 2001; Wolf et

TABLE 1
1500 Å LF PARAMETERS FOR ($\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$) AND $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$

z Bin	Number	M_{bias}	α	M_*	Φ_* (10^{-3} Mpc^{-3})
0.055 ^a	896	...	-1.21 ± 0.07	-18.05 ± 0.11	4.07 ± 0.56
0.2–0.4.....	319	-15.36	-1.19 ± 0.15	-18.38 ± 0.25	6.15 ± 1.76
0.4–0.6.....	258	-16.85	-1.55 ± 0.21	-19.49 ± 0.37	1.69 ± 0.88
0.6–0.8.....	274	-17.91	-1.60 ± 0.26	-19.84 ± 0.40	1.67 ± 0.95
0.8–1.2.....	188	-18.92	-1.63 ± 0.45	-20.11 ± 0.45	1.14 ± 0.76
0.2–0.5 ^b	137	...	-1.40 ± 0.20	$-18.94^{+0.34}_{-0.42}$	$0.99^{+0.58}_{-0.46}$
0.5–0.8 ^b	93	...	-1.40 ± 0.20	$-19.57^{+0.22}_{-0.31}$	$0.58^{+0.22}_{-0.20}$
0.8–1.2 ^b	59	...	-1.40 ± 0.20	$-20.01^{+0.24}_{-0.27}$	$0.45^{+0.10}_{-0.10}$
0.2–0.5 ^c	153	...	-1.50 ± 0.20	$-18.80^{+0.33}_{-0.42}$	$0.90^{+0.56}_{-0.43}$
0.5–0.8 ^c	120	...	-1.50 ± 0.20	$-19.50^{+0.23}_{-0.27}$	$0.63^{+0.26}_{-0.23}$
0.8–1.2 ^c	28	...	-1.50 ± 0.20	$-20.20^{+0.36}_{-0.44}$	$0.16^{+0.04}_{-0.04}$
0.2–0.5 ^d	152	...	-1.50 ± 0.20	$-19.53^{+0.39}_{-0.51}$	$0.60^{+0.45}_{-0.32}$
0.5–0.8 ^d	196	...	-1.50 ± 0.20	$-19.63^{+0.23}_{-0.27}$	$1.03^{+0.42}_{-0.37}$
0.8–1.2 ^d	101	...	-1.50 ± 0.20	$-19.89^{+0.19}_{-0.21}$	$0.80^{+0.18}_{-0.19}$
1.75–2.25 ^e	139	-17.54	-1.49 ± 0.24	-20.33 ± 0.50	2.65 ± 2.00
2.40–3.40 ^e	173	-18.17	-1.47 ± 0.21	-21.08 ± 0.45	1.62 ± 0.90
2.50–3.50 ^f	564	...	-1.60 ± 0.13	-21.07 ± 0.15	1.40

^a Local sample with $z \leq 0.1$ and $FUV \leq 20$.

^b $(B - I) \geq 0.85$ sample with $NUV \leq 24.5$.

^c $0.56 \leq (B - I) \leq 0.85$ sample with $NUV \leq 24.5$.

^d $(B - I) \leq 0.56$ sample with $NUV \leq 24.5$.

^e HDF sample with $F450 \leq 27$ and $F606 \leq 27$.

^f LBG sample with $R \leq 25$.

al. 2003). In this section, we explore the FUV LF and its evolution as a function of color.

As shown by Salim et al. (2005), rest-frame $(NUV - R)$ is tightly correlated with the ratio of current to past averaged SFR, implying that the star formation history of a galaxy can already be constrained using a single color. In Figure 4, we plot the $(NUV - R)$ versus $(B - I)$ rest frame as well as the location of theoretical SEDs from elliptical to Sd (Poggianti 1997; *filled circles*), observed irregular (Coleman et al. 1980; *filled circles*), and starbursts (Kinney et al. 1996; *filled triangles*).

As $(B - I)$ correlates with $(NUV - R)$ (Fig. 4) and is not affected by the UV flux uncertainties mentioned above, we use $(B - I)$ as a proxy for spectral types. We note, however, the degeneracy between dust and age of the stellar population: dusty starbursts (SB3 to SB6; *filled triangles*) cannot be distinguished from spiral galaxies (*filled circles*) using $(B - I)$. Eliminating this degeneracy will require additional color information sensitive to the old star population (e.g., K -band flux) not available in the present data set.

We split our sample into three classes: $(B - I) \leq 0.56$ (corresponding to unobscured starbursts), $0.56 \leq (B - I) \leq 0.85$ (corresponding to Irr to Sd galaxies with a contamination of obscured starbursts), and $(B - I) \geq 0.85$ (corresponding to Sd to Sb galaxies with a contamination of obscured starbursts and a negligible 7% contribution of types earlier than Sb). The shortage of red systems in our sample is consistent with the morphological analysis of de Mello et al. (2004) based on a small NUV rest-frame sample (34 objects) in the Chandra Deep Field–South observed with the *Hubble Space Telescope* (Advanced Camera for Surveys). The authors only found two early-type galaxies (8%), the rest being late types (32%) and starbursts (60%).

In the bottom panel of Figure 4, we show the relative fraction for each color class in three redshift bins: $0.2 \leq z \leq 0.5$, $0.5 \leq z \leq 0.8$, $0.8 \leq z \leq 1.2$. We extend our analysis to lower z by applying the same criteria to the *GALEX*-SDSS fields for galaxies with $z_{\text{phot}} \leq 0.2$ and $FUV \leq 22$ (*filled squares*). We find that the contribution of unobscured starbursts rises from $\sim 12\%$ at $z \sim 0.1$ to 55% at $z \sim 1$, while the fractions of the two other classes decrease. (The reddest class actually seems to increase again at $z \sim 1$, but this may reflect a classification bias since the I band probes the emitted light below the 4000 Å break and does not trace reliably the old stellar population).

We measure the LFs for the three classes. Because of the small number of galaxies, we fixed the slopes to $\alpha = -1.4 \pm 0.2$ for our reddest class and $\alpha = -1.5 \pm 0.2$ for the two others, in agreement with the values obtained in the range $0.2 \leq z \leq 0.5$. These values are consistent with the slopes derived by Wolf et

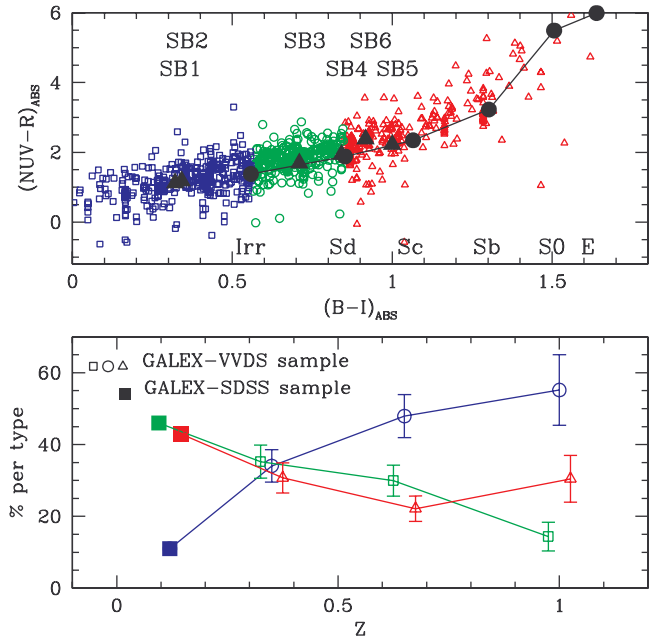


FIG. 4.—Rest-frame color-color plot for the color classification (*top panel*) and the fraction of galaxy classes vs. redshift (*bottom panel*).

al. (2003) at 2800 Å for their types 2–4. The best-fit STY parameters are listed in Table 1 and in Figure 3.

We find that the bluest class (unobscured starbursts) evolves less strongly in luminosity than the two other classes ($\Delta M_* \leq -0.5$ mag in the range $0.35 \leq z \leq 1.0$ as opposed to $\Delta M_* \geq -1$ mag). On the other hand, the number densities [$\rho = \int_{-\infty}^{M_{\text{cut}}} \Phi(M) dM$ with $M_{\text{cut}} = -18.5$] evolve similarly to the non-volume-corrected fractions shown in Figure 4; namely, the density of unobscured starbursts increases sharply with z while that of the reddest classes decreases.

The interpretation of our results in terms of SFR evolution is presented in a companion paper by Schiminovich et al. (2005).

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