THE GALEX-VVDS MEASUREMENT OF THE EVOLUTION OF THE FAR-ULTRAVIOLET LUMINOSITY DENSITY AND THE COSMIC STAR FORMATION RATE


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ABSTRACT

In a companion paper (Arnouts et al. 2004) we presented new measurements of the galaxy luminosity function at 1500Å out to z~1 using GALEX-VVDS observations (1039 galaxies with NUV≤24.5 and z>0.2) and at higher z using existing data sets. In this paper we use the same sample to study evolution of the FUV luminosity density ρ1500. We detect evolution consistent with a (1+z)^2.5±0.7 rise to z~1 and (1+z)^0.3±0.4 for z>1. The luminosity density from the most UV-luminous galaxies (UVLG) is undergoing dramatic evolution (∼30) between 0<z<1. UVLGs are responsible for a significant fraction (>25%) of the total FUV luminosity density at z~1. We measure dust attenuation and star formation rates of our sample galaxies and determine the star formation rate density (ρSFR) as a function of redshift, both uncorrected and corrected for dust. We find good agreement with other measures of ρSFR in the rest ultraviolet and Hα given the still significant uncertainties in the attenuation correction.

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

1. INTRODUCTION

2. DATA

The rest-frame far-ultraviolet (FUV: 1500Å) luminosity has been used to determine the star formation rate (SFR) of stellar populations over the complete range of redshifts for which galaxies have been observed. The utility and limitations of the integrated measures—the FUV luminosity function (φFUV) and luminosity density (ρFUV)—and their relation to the star formation history of the universe has been extensively discussed and reviewed (e.g. Madau, Pozzetti, & Dickinson 1998, Hopkins 2004). A principal goal of the Galaxy Evolution Explorer (GALEX) mission (Martin et al. 2004) is to perform deep wide-angle surveys to obtain an accurate measurement of the FUV luminosity density over the range 0 < z < 1 and beyond. In this letter we present results from a small pilot study performed in the 2h VIRMOS-VLT Deep Survey field using measurements from 1039 galaxies.

GALEX data will allow us to determine how the rest-UV can best be used to study the detailed properties of galaxies (e.g. dust, metallicity, star formation history). Since this is work in progress, here we will instead use existing methods to determine the intrinsic luminosity of galaxies in the FUV (Meurer, Heckman, & Calzetti 1999, hereafter MHC99, for dust corrections) and the SFR that luminosity implies (Kennicutt 1998 for SFR conversion). This simple analysis yields some quick answers—we will discuss how this work will be expanded and developed in the near future.

Throughout this paper we adopt the flat-lambda cosmology (ΩM = 0.3, ΩΛ = 0.7) with H0 = 70 km s⁻¹ Mpc⁻¹.
from the GALEX-VVDS sample in four redshift bins. Lyman Break Galaxy (LBG) sample from Arnouts et al. (2002). For comparison we observed October-November 2004 as part of the GALEX Deep Survey. Filled circles from \( \rho_{1500} \) integrated from \( z_{\text{min}} \) to \( z \) show significant evolution. Dotted, solid and dashed lines correspond to the FUV luminosity density vs. redshift. Filled circles indicate fraction of luminosity emitted by galaxies brighter than \( 0.2L_{z=3} \) or \( M_{\text{FUV}} \) -19.32. Colors same as Figure 1. Vertical hatched bars indicate fraction of luminosity emitted by galaxies brighter than \( 0.2L_{z=3} \). Red dashed line shows QSO FUV LD using values from Boyle et al. (2000) and Madau et al. (1999). Solid line same as Figure 1.

\[ \rho = \int_{L_{\text{min}}}^{\infty} dLL\phi(L) \]

with \( L_{\text{min}} = 0 \) \( (\rho = \phi_\alpha L_\alpha (\alpha + 2)) \). Although this quantity is strongly dependent on uncertainties in the faint end slope (\( \alpha \)), it allows direct comparison with other measurements of \( \rho_{1500} \) and the star formation rate density, \( \rho_* \). Fits and errors were determined using the ALF tool (Ilbert et al., 2004) with error bars based on the extreme values of the LD calculated at each point on the \( \alpha-M_* \) 1\( \sigma \) error contour. The \( z \)\( =1.0 \) bin, our best Schechter function fit yielded large errors for the slope (\( \alpha=-1.63^{+0.45}_{-0.43} \)). For this bin we fixed the faint end slope at \( \alpha = -1.6 \), adopting the value used in high-\( z \) studies (e.g. Steidel et al. 1999) and consistent within errors with our own values at lower and higher \( z \). Total \( \rho_{1500} \) shows significant \( \sim (1+z)^{2.5} \) evolution out to \( z=1 \), with evidence for a shallow continued rise out to \( z=3 \). This evolution is discussed further in the next section. Two points are worth noting regarding the comparison of LD at different redshifts. First, as demonstrated in (Paper I) and discussed below, the galaxy population that contributes most of the LD varies (vs. color, luminosity) with redshift. Secondly, while most of the sample is UV-selected, the Steidel et al. (1999) LBG galaxies were color-selected and the \( z=3 \) LD value may be missing some fraction of the UV light. The similarity between the \( z=2.9 \) and \( z=3 \) data points suggests that the missing fraction is small.

We explore the contribution to the luminosity density (\( < z > = 0.3, 0.5, 0.7, 1.0 \)), and also determined values for the HDF sample (\( < z > = 2.0, 2.9 \)). Results are shown in Table 1 and plotted in Figure 1. We chose to calculate \( \rho_{1500} \) in several ways. First, we summed \( \phi(L)\sigma(L) \) using the LF obtained from the \( V_{\max} \) method. Because luminosity bins with no detections do not contribute we consider this a lower limit on \( \rho_{1500} \). We also calculated a “total” luminosity density by integrating Schechter function fits to the LF using the formula:

3. LUMINOSITY DENSITY

We calculated the FUV luminosity density \( \rho_{1500} \) from the GALEX-VVDS sample in four redshift bins

\begin{table}
\centering
\caption{FUV 1500Å Luminosity Density}
\begin{tabular}{lcccc}
\hline
\( z \) & \( \log \rho_{1500} \) & \( \log \rho_{1500} \) & \( \log \rho_{1500} \) & \( \log \rho_{1500} \) \\
\hline
& total & \( V_{\max} \) & \( L > L_{\text{min}} \) & \\
\hline
0.055 & 25.54 & -0.05 & 25.54 & -0.05 & 23.97 \\
0.3 & 25.86 & -0.03 & 25.86 & -0.03 & 24.67 & -0.17 \\
0.5 & 25.97 & -0.04 & 25.97 & -0.04 & 25.20 & -0.09 \\
0.7 & 26.16 & -0.01 & 26.16 & -0.01 & 25.48 & -0.05 \\
1.0 & 26.11 & -0.03 & 26.11 & -0.03 & 25.51 & -0.05 \\
2.0 & 26.45 & -0.09 & 26.45 & -0.09 & 26.03 & -0.12 \\
2.9 & 26.52 & -0.13 & 26.52 & -0.13 & 26.26 & -0.08 \\
3.0 & 25.58 & -0.17 & 25.58 & -0.17 & 26.22 \\
\hline
\end{tabular}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{f1}
\caption{FUV luminosity density vs. redshift. Filled circles indicate LF fit to full sample with unconstrained slope \( \alpha \). Filled squares denote LF fit with fixed \( \alpha = -1.6 \). Purple (GALEX) and dark green (HDF) symbols are from this work. Black dot is taken from local LF (Wyder et al. 2004) and green square from Steidel et al. (1999). Open circles denote \( \rho_{1500} \) determined using \( V_{\max} \). Lines indicate \( (1+z)^n \) evolution. Dotted, solid and dashed lines correspond to \( n = 1.5, 2.5, 3.5 \) respectively.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{f2}
\caption{FUV luminosity density of ultraviolet luminous galaxies (UVLGS) vs. redshift and comparison w/ QSO luminosity density. Filled circles from \( \rho_{1500,\text{FUV LGS}} \) integrated from \( z_{\text{min}} = 0.2L_{z=3} \) or \( M_{\text{FUV}} \) -19.32. Colors same as Figure 1. Vertical hatched bars indicate fraction of luminosity emitted by galaxies brighter than \( 0.2L_{z=3} \). Red dashed line shows QSO FUV LD using values from Boyle et al. (2000) and Madau et al. (1999). Solid line same as Figure 1.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{f3}
\caption{FUV luminosity density vs. redshift. Filled circles indicate LF fit to full sample with unconstrained slope \( \alpha \). Filled squares denote LF fit with fixed \( \alpha = -1.6 \). Purple (GALEX) and dark green (HDF) symbols are from this work. Black dot is taken from local LF (Wyder et al. 2004) and green square from Steidel et al. (1999). Open circles denote \( \rho_{1500} \) determined using \( V_{\max} \). Lines indicate \( (1+z)^n \) evolution. Dotted, solid and dashed lines correspond to \( n = 1.5, 2.5, 3.5 \) respectively.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{f4}
\caption{FUV luminosity density of ultraviolet luminous galaxies (UVLGS) vs. redshift and comparison w/ QSO luminosity density. Filled circles from \( \rho_{1500,\text{FUV LGS}} \) integrated from \( z_{\text{min}} = 0.2L_{z=3} \) or \( M_{\text{FUV}} \) -19.32. Colors same as Figure 1. Vertical hatched bars indicate fraction of luminosity emitted by galaxies brighter than \( 0.2L_{z=3} \). Red dashed line shows QSO FUV LD using values from Boyle et al. (2000) and Madau et al. (1999). Solid line same as Figure 1.}
\end{figure}

GALEX observations of the VVDS 0226-04 field (0226m00s -04°30’00”, J2000) were performed in October-November 2004 as part of the GALEX Deep Imaging Survey. Further details of these observations, the subsequent match to VVDS spectroscopy and photometry and the calculation of the LF can be found in the companion letter Arnouts et al. (2004) (hereafter Paper I) and references therein. Paper I also describes the derivation of the \( \phi_{\text{FUV}} \) at \( z=2.0 \) and 2.9 using an HDF sample from Arnouts et al. (2002). For comparison we also use the local \( \phi_{\text{FUV}} \) (Wyder et al. 2004) and the \( z=3 \) Lyman Break Galaxy (LBG) \( \phi_{\text{FUV}} \) (Steidel et al. 1999).
from UV luminous galaxies (UVLGs) by measuring the luminosity density from galaxies with $L > L_{\text{min}}$. To facilitate comparison with high-z studies, we set $L_{\text{min}} = 0.2L_{\odot}z=3$ ($M_{\text{min}} = -19.32$) from Steidel et al. (1999), also adopted by Giavalisco et al. (2004) for their work. These galaxies are observable in all redshift ranges and therefore there is no additional uncertainty related to extrapolation beyond the faintest observed magnitude. Figure 2 highlights the dramatic evolution of $\rho_{1500,\text{UVLG}}$ increasing by $\times 30$ to $z = 1$ or $(1+z)^5$. Furthermore we find that UVLGs are a major contributor to $\rho_{1500}$ at $z = 1$ with a fractional contribution, $\rho_{1500,\text{UVLG}}/\rho_{1500}$ of 25%. We plot for comparison $\rho_{1500,\text{QSO}}$ using the functional form of the QSO LD evolution (in the B-band) from Boyle et al. (2000) and the QSO SED from Madau, Haardt, & Rees (1999) which has a shallower evolutionary slope (3.5) vs. UVLGs (5) for $z < 1$.

4. STAR FORMATION RATE DENSITY

To determine intrinsic ultraviolet luminosities for the GALEX-VVDS sample, we apply the MHC99 dust attenuation formula:

$$A_{\text{FUV}} = 4.43 + 1.99(\beta) = 4.49 + 1.97(\beta_{\text{GLX}})$$

where we use the definition of $\beta_{\text{GLX}}$, the FUV slope calculated using the rest-frame GALEX FUV and NUV bands, from Kong et al. (2004). We only calculate $\beta_{\text{GLX}}$ for the subset of galaxies observed in U-band (888 galaxies). Typical errors are $\sigma_\beta \sim 0.4$. Figure 3 shows the distribution of the k-corrected $\beta_{\text{GLX}}$. The full sample has median $\beta_{\text{GLX}} = -1.64$, $\text{FWHM}(\beta) = 1.4$ with little variation with redshift. We find good agreement with measurements of $\beta$ at low-z ($< \beta > = -1.6$ for a FUV selected sample; Treyster et al. 2004) and high-z (Adelberger & Steidel 2000).

Within our own sample we might have expected to see an increase of $\beta_{\text{GLX}}$ vs. $z$ since high luminosity galaxies—which dominate the high-z bins—are expected to show significant attenuation. Several effects could

21 This luminosity corresponds to $10^{10.1} L_\odot$, $\sim 2/3$ the luminosity limit ($10^{10.3} L_\odot$) adopted for UVLGs in Heckman et al. (2004).

work against this trend. We are detecting galaxies close to the NUV band confusion limit (beam/source $\sim 10$ for NUV$<25$) and source blending could shift UV-optical colors and the slope blueward. We performed tests which conservatively apportioned NUV flux among all potential optical counterparts and set a limit on the offset of the median $\Delta \beta_{\text{GLX,blend}} \leq 0.35$. This is consistent with the median $\beta_{\text{GLX}} = -1.44$ measured for “isolated” UV detections with only a single optical counterpart (see Figure 3). (However, we can’t neglect the possibility that some fraction with multiple counterparts are physical pairs which could show a different distribution of $\beta_{\text{GLX}}$.) We also note that the MHC99 $A_{\text{FUV}} - \beta$ relation was determined for starbursting galaxies (the bulk of our sample, see Paper I) but might overestimate the conservative attenuation for normal star forming galaxies (Bell 2002; Kong et al. 2004) which are found in our lowest redshift bins. For a conservative measurement of the average attenuation in our whole sample, we use the “isolated” subsample, and calculate a mean attenuation factor of $\times 7$ ($A_{\text{emean}} = 1.8$) where we have estimated and applied a bias correction to the mean ($\times 0.7$) due to non-negligible $\sigma_\beta$. We also adopt a ‘minimum attenuation’ $A_{\text{FUV}} = 1$ which may be more representative of a full UV-selected population (Buat et al. 2004).

The SFR was calculated for each galaxy using:

$$SFR(M_\odot \text{yr}^{-1}) = 1.4 \times 10^{-28} L_{\text{FUV}} (\text{erg s}^{-1} \text{Hz}^{-1})$$

from Kennicutt (1998). In Figure 4 we plot the SFR derived for each galaxy using the uncorrected and the dust-corrected FUV luminosities. Our sample shows no dependence of dust attenuation with SFR$^{\text{uncorr}}$ and as a
comparison measurements obtained using spectroscopic
we converted $\rho$ SDSS (Brinchmann et al. 2003) and other recent studies
dependent derivations using 2dF (Baldry et al. 2002),
$\beta$ evol $\sigma^2$ blue triangles from Wilson et al. (2002) for
measurements at 1500 $\AA$ for $z < 0.6$ and $1 + z > 1$ based on chi-
sharpened fit to our sample (see inset; $\sigma$ and 2$\sigma$ confidence contours
shown). Shaded region shows range corresponding to max/min dust-attenuation. Filled red stars from dust-corrected H$\alpha$
measurements (with increasing redshift) from Pérez-González et al.
(2002). Open red star from SDSS (H$\alpha$/emission line) Brinchmann et al. 2004.

consequence we find higher attenuation in galaxies with
high SFR$^{corr}$. This paucity of low-attenuation galaxies with high SFR$^{corr}$ has been noted in previous studies
(e.g. Wang & Heckman 1996, Adelberger & Steidel 2000). Some of the observed effect may also be
due to the scatter in $A$ FUV discussed above (resulting in a tail of high $A$ FUV galaxies) and/or limitations of the dust attenuation law. We plot $\rho_\star(z)$ (derived from $\rho_{1500}$ with no dust correction) in Figure 5. Measurements from this paper were fit using the parametrization from Baldry et al. (2002) ($\rho_\star(z) \sim (1 + z)^{\beta_{evol}, z < 1}$ and $\rho_\star(z) \sim (1 + z)^{\alpha_{evol}, z > 1}$). We find a best-fit $\beta_{evol} = 2.5 \pm 0.7$, $\alpha_{evol} = 0.5 \pm 0.4$. The $\sigma$ constraint on the ($\alpha_{evol}, \beta_{evol}$) pair is consistent with independent derivations using 2dF (Baldry et al. 2002), SDSS (Brinchmann et al. 2003) and other recent studies (c.f. Fig. 13 Baldry et al. 2002).

Several uncorrected (blue) and dust-corrected (red)
comparison measurements obtained using spectroscopic redshifts are shown in Figure 5. Before determining $\rho_\star$, we converted $\rho_{2000}$ (Sullivan et al. 2000, Lilly et al. 1996) and $\rho_{2500}$ (Wilson et al. 2002, $\alpha = -1.5$ data)
to $\rho_{1500}$ using $\rho(\lambda)$ obtained from local $\rho_{1540}$ and $\rho_{2300}$
by Wyder et al. 2004 ($\sim \lambda^{0.3}$). Wilson et al. (2002) and Lilly et al. (1996) both show good agreement with our measured values despite the difference in evolutionary slope obtained in the two studies ($\beta_{evol} \sim 1.7 \pm 1$, $3.3 \pm 0.7$, respectively). The local luminosity density reported by Sullivan (2000) appears high, as noted in Wyder et al. (2004). Finally, we show a likely range of dust-corrected SFR densities, applying the average $A_{min}^FUV$, $A_{mean}^FUV$ to the best-fit parametrized $\rho_\star(z)$. Using the Kennicutt (1998) SFR conversion, we find that recent dust-corrected H$\alpha$ measurements fall within our attenuation-corrected range. Although we have implicitly assumed no evolution in the dust correction, we emphasize that for UV flux-limited samples we might expect evolution in the average dust-attenuation correction vs. redshift and will explore this further in future work.

The FUV is tracing a predominantly homogeneous population (star-forming and starbursting) making interpretation of integrated measures much more straightforward than at longer wavelengths (cf. Wolf et al. 2003). We have shown that a significant population of UVLGS lies within easy reach ($0.6 < z < 1.2$). We will compare these unique star-forming galaxies with their high-redshift LBG analogs (e.g. Shapley et al. 2003). In the near future our sample will expand by $\times 5$ in this field alone, and by more than $\times 100$ using data from redshift surveys across the sky. In some locations we will increase our depth to $m_A \sim 26$ as part of the Ultra-Deep Imaging Survey and probe down to 0.1L$_\odot$ (see Figure 4) to better constrain the faint end of $\Phi_{FUV}$. This will be supplemented by an even larger catalog ($>10^8$ objects) with photometric redshifts. We will soon be able determine how SFR evolution depends on environment, morphology and spectral type and will examine our results within the context of cosmological simulations. A major challenge lies in the understanding of the role of dust obscuration, one which we will explore using recent, more sophisticated models (e.g. Kong et al. 2004) as the GALEX surveys continue.

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