THE ULTRAVIOLET GALAXY LUMINOSITY FUNCTION FROM GALEX DATA: COLOR-DEPENDENT EVOLUTION AT LOW REDSHIFT

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ABSTRACT

We present measurements of the far-UV (FUV; 1530 Å) and near-UV (NUV; 2310 Å) galaxy luminosity functions (LFs) at low redshift (z ≤ 0.2) from Galaxy Evolution Explorer observations matched to the Two-Degree Field (2dF) Galaxy Redshift Survey. We split our FUV and NUV samples into two UV − bh color bins and two redshift bins. As observed at optical wavelengths, the local LF of the bluest galaxies tend to have steeper faint-end slopes and fainter characteristic magnitudes M* than the reddest subsamples. We find evidence for color-dependent evolution at very low redshift in both bands, with bright blue galaxies becoming dominant in the highest redshift bin. The evolution of the total LF is consistent with an ~0.3 mag brightening between z ∼ 0 and 0.13, in agreement with the first analysis of deeper GALEX fields probing adjacent and higher redshifts.

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

1. INTRODUCTION

The importance of estimating luminosity functions (LFs) as a function of redshift, color, environment, wavelength, etc., to understand galaxy formation and evolution has been well emphasized in the literature. Multivariate luminosity functions are crucial to constrain theoretical models on small scales, where the physics is most complex. The shape of the galaxy LFs results from nontrivial physical processes (Benson et al. 2003; Binney 2004), and understanding their evolution is a challenging task for numerical simulations (e.g., Nagamine et al. 2001). The Galaxy Evolution Explorer (GALEX) mission has recently opened a new field of constraints by allowing such statistical measures as LFs to be performed in the rest-frame ultraviolet (UV) in what is now considered the low-redshift universe (z < 1−2), where most of the evolution of galaxies is thought to have taken place.

In this Letter, we use data from the GALEX All-sky Imaging Survey matched to spectroscopic data from the Two-Degree Field Galaxy Redshift Survey (2dFGRS) to investigate the color properties of local UV-selected galaxies and the color dependence and evolution of their LF at very low redshift (z < 0.2). Whereas much effort has been devoted to estimate the evolution of galaxy light over the widest and furthest range of redshift possible, very few surveys have allowed us to probe evolution at recent epochs (Loveday 2004), and none so far at UV wavelengths. This work is a companion paper to Wyder et al. (2005, hereafter Paper I), who present the total LFs of FUV- and NUV-selected galaxies in the local (z ≤ 0.1) universe. It also complements the work of Arnouts et al. (2005), Schiminovich et al. (2005), and Budavári et al. (2005), who quantify the evolution of the UV LF at higher redshift using the GALEX Medium and Deep Imaging Surveys.

The data are summarized in § 2. Section 3 presents the color properties of the samples. We estimate and discuss the dependence of the UV LFs on galaxy color and redshift at recent epoch in § 4. We assumed a flat ΛCDM cosmology with H₀ = 70 km s⁻¹ Mpc⁻¹, Ω₀ = 0.3, and Ωₐ = 0.7.

2. DATA

The GALEX field of view has a diameter of 1°2, and each pointing is imaged simultaneously in both the far-UV (FUV) and near-UV (NUV) bands with effective wavelengths of 1530 and 2310 Å, respectively. The GALEX instruments and mission are described by Morrissey et al. (2005) and Martin et al. (2005).

The specific data analyzed in this paper are presented in Paper I. In brief, they consist of 133 GALEX All-sky Imaging Survey pointings overlapping the 2dFGRS (Colless et al. 2001) in the south Galactic pole region. As the NUV images are substantially deeper than the FUV, we used the NUV images for detection and measured the FUV flux in the same aperture as for the NUV. The apparent magnitudes were corrected for foreground extinction using the Schlegel et al. (1998) reddening maps and assuming the extinction law of Cardelli et al. (1989).

The GALEX catalogs were matched with the 2dF catalog using a search radius of 6″. We restricted the sample to areas with effective exposure times tₑ > 60 s and removed sources with magnitude errors greater than 0.4 or that were contaminated by artifacts from bright stars. We also removed overlap regions by restricting the coverage to the inner 0°45 of each field. Finally, we excluded GALEX sources where the 2dF redshift completeness was less than 80%, and also areas of the sky excluded from the 2dF input catalog. Our final working area of GALEX-2dF overlap is 56.73 deg² in both bands.
We applied a faint magnitude limit of 20 in both bands, corresponding to the bluest $UV - b_j$ color observed, and beyond which the redshift completeness begins to drop. (Note that $b_j$ was shifted by $-0.051$ into the AB system. All quoted magnitudes are AB). We also applied a bright magnitude limit of 17 to avoid extended sources with potential photometric problems. We visually inspected the resulting catalog of 2dF spectra and further removed 27 objects with broad emission lines (the obvious AGNs/QSOs). Our final catalogs consist of 1292 FUV-selected galaxies and 1869 NUV-selected galaxies with $17 \leq UV \leq 20$ and available $b_j$ magnitude and 2dF redshift (with 2dF redshift quality parameter $\geq 3$). Both redshift distributions extend to $z \sim 0.25$ (Paper I). FUV fluxes are available for all but one of the galaxies in the NUV-selected sample, although uncertainties can be quite large for the faintest objects.

3. COLOR PROPERTIES

Figure 1 shows color-color diagrams ($FUV - NUV$ vs. $FUV - b_j$) for the FUV- and NUV-selected samples (left and right panels, respectively). Typical error bars are shown in the upper left corners. The thin lines are a set of 42 spectral energy distribution (SED) models by Bruzual & Charlot (2003, hereafter BC) from old ellipticals (in red) to young irregular galaxies, assuming a range of star formation histories ($\tau = 1$ Gyr to $\infty$), ages (0.1–12 Gyr), metallicities (0.2–1 $Z_{\odot}$), and extinctions ($A_v = 0$–1.5). The thick dashed lines are dust-free SED models by Poggianti (1997). The tracks show the color evolution of the various galaxy types from $z = 0$ to 0.25 (roughly counterclockwise).

The bulk of both samples is consistent with bona fide late-type galaxies, with only a handful of objects displaying elliptical-like colors. We do not observe any source with “UV-optical excess” colors (bluer than the bluest model) such as were observed in the FOCA sample (Treyer et al. 1998; Sullivan et al. 2000), suggesting that the so-called excess was to be found in the estimate of the UV flux of these objects, rather than in some physical explanation. On the other hand, we find a small fraction of galaxies with $FUV - NUV$ colors somewhat bluer than any model ($\sim 15\%$ in the FUV-selected sample, $\sim 7\%$ in the NUV-selected sample). This is partly because of newly measured, small but opposite offsets in the FUV and NUV calibrations, adding up to $+0.13$ in $FUV - NUV$ (new in-flight calibrations; P. Morissey 2004, private communication) not applied in the current catalogs.

But shortcomings in the models at UV wavelengths cannot be ruled out. Despite the wide coverage in parameter space, the data are not fully accounted for (e.g., the reddest sources in both $FUV - NUV$ and $FUV - b_j$). Figure 1 suggests that UV-selected galaxies may require alternative model ingredients (e.g., more erratic star formation histories, as suggested by Sullivan et al. 2003).

We assign a best-fit SED (drawn from the combined and interpolated BC and Poggianti libraries) to each galaxy using its redshift and two independent colors ($FUV - NUV$ and $FUV - b_j$). Figure 2 shows the model $k$-corrections in the $b_j$, $FUV$, and $NUV$ bands (thin solid lines for BC, and thick dashed lines for Poggianti).

UV $k$-corrections are small enough for the late-type, low-redshift galaxies dominating the sample (as opposed to $k$-corrections in optical bands) that uncertainties on the assigned SEDs have negligible impact on the resulting LFs.

We can also fit a power law through the two bandpasses and derive a spectral index for each galaxy [$\beta = (FUV - NUV)/0.425 - 2$, assuming $F_\lambda \propto \lambda^\beta$]. The mean spectral indices of the FUV- and NUV-selected samples are $\langle \beta \rangle \sim -1.6$ and $-1.3$, respectively. The UV slope $\beta$ has been shown to be a good tracer of dust attenuation in galaxies undergoing a strong starburst, but not so reliably in others (Bell 2002; Kong et al. 2004). In particular, Buat et al. (2005) found that local NUV-selected galaxies tend to have lower attenuations than starbursts for a given slope. As our two samples exhibit slopes corre-
responding to low attenuations in pure starburst galaxies, we conclude that they must be very little affected by dust (see Paper I for a quantitative discussion).

4. COLOR AND z-DEPENDENT LUMINOSITY FUNCTIONS

We split both samples into two rest-frame color bins: (FUV $- b_j)_{0,0} \leq z \geq 2$ (roughly corresponding to an Sb spectral type and to the mean of the color distribution), referred to as blue and red subsamples, respectively. We further split each of these subsamples into two redshift bins: $z \leq 0.1$ and $0.1 \leq z \leq 0.2$, referred to as low and “higher” redshift subsamples, respectively. The mean redshifts in these two bins are 0.055 and 0.12, respectively, for the FUV sample, and 0.057 and 0.13 for the NUV sample. As in Paper I, the redshift completeness is defined as the ratio of UV objects matched to a 2dFGRS counterpart with (high quality) redshift to the total number of UV galaxies in a given magnitude bin, as computed by Xu et al. (2005) using $(V)/H_{11506}$ for the NUV sample.

In the Sloan Digital Sky Survey (SDSS) star/galaxy separation criteria in overlap regions. It is roughly constant over the range $17 \leq UV \leq 20$ in both bands, with mean values of $\sim 79\%$ in the NUV and $92\%$ in the FUV (see Fig. 1 in Paper I). We computed binned luminosity functions using the traditional $V_{max}$ estimator (Feltlen 1976) in the 12 subsamples (blue, red, and total at low and higher $z$ in both bands), and derived best-fit Schechter functions (Schechter 1976) for each of them. Since the magnitude range in the highest redshift slice is too bright and narrow to constrain the slope meaningfully, we fixed it to the low-redshift value in each case.

Results are shown in Figure 3, and the best-fit Schechter function parameters are listed in Table 1.

The FOCA 2000 Å LF (Sullivan et al. 2000) at a mean redshift $z \sim 0.15$ is also plotted for comparison (converted to the AB-magnitude system and to our $H_0$ value, but without accounting for the difference in bandpasses). We refer to Paper I for a discussion on the discrepancy between the FOCA and GALEX LFs. As observed at optical wavelengths (Madgwick et al. 2002; Nakamura et al. 2003), the local LFs of the bluest galaxies tend to have steeper faint-end slopes and fainter characteristic magnitudes $M_*$ than the redder subsamples (although our definition of red would qualify as blue in optically selected samples). The fact that the latest types are observed to fainter absolute magnitudes than the earlier types induces a small bias in the estimate of the faint-end slope of the full sample. The dotted lines in the upper panels of Figure 3 show that the sum of the blue and red LFs is slightly steeper at the faint end than estimated for the galaxy population as a whole, because of the shortage of red galaxies in the faintest bins.

The total FUV and NUV LFs in the highest redshift bin (Fig. 3, lower panels) are both consistent with $\sim 0.3$ mag brightening in $M_*$ with respect to the LFs at $z < 0.1$. This evolution is quite similar to that found in optically selected samples at the same redshifts (Loveday 2004).

Evolution can also be inferred from the steeply rising $V/V_{max}$ distribution of both $z$-unlimited samples (with $V/V_{max} = 0.54$ in both bands instead of the 0.5 expected from a nonevolving population). As the redshift distributions show two strong peaks around 0.06 and 0.11 (Paper I), the appearance of evolution could be attributed to large-scale structure effects, but removing these two structures from the samples did not affect our results.

Evolution also seems to occur predominantly in the blue subsamples, with blue galaxies dominating the bright end of the LF in the highest $z$ bin. We checked that no color trend was observed as a function of $b_j$, as might be expected if the 2dFGRS was strongly biased against, e.g., faint blue low surface brightness galaxies (LSBGs), making bright blue galaxies seem dominant at higher redshift. The issue of missing galaxies in the 2dFGRS, in particular LSBGs, has been addressed in a number of papers, most recently by Cross et al. (2004). The authors find that the survey does indeed miss $\sim 15\%$ of the galaxy population, of which only $6\%$ are identified as LSBGs. If this particular class of objects is unlikely to affect our results, the remaining missing galaxies may bias our analysis, should their redshift distribution look different from the one actually measured. A truly UV-selected spectroscopic survey is under way to address this question.

The present results are consistent with the FUV analysis of a much deeper GALEX field probing adjacent and higher redshifts (Arnouts et al. 2005; Schiminovich et al. 2005). They are also in rough agreement with the rate of evolution derived

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**Table 1**

| Band   | $z$   | Type   | $M_*$  | $-\alpha$ | log $\Phi_*$ |
|--------|-------|--------|--------|-----------|-------------|
| FUV    | 0.0–0.1| All    | $-18.04 \pm 0.11$ | $1.22 \pm 0.07$ | $-3.23 \pm 0.06$ |
|        | 0.1–0.2|        | $-18.31 \pm 0.06$ |          | $-3.33 \pm 0.07$ |
|        | 0.0–0.1| Blue   | $-17.89 \pm 0.15$ | $1.29 \pm 0.09$ | $-2.54 \pm 0.09$ |
|        | 0.1–0.2|        | $-18.44 \pm 0.09$ |          | $-2.73 \pm 0.10$ |
|        | 0.0–0.1| Red    | $-18.19 \pm 0.22$ | $1.10 \pm 0.17$ | $-2.80 \pm 0.12$ |
|        | 0.1–0.2|        | $-18.15 \pm 0.08$ |          | $-2.50 \pm 0.10$ |
| NUV    | 0.0–0.1| All    | $-18.23 \pm 0.11$ | $1.16 \pm 0.07$ | $-2.26 \pm 0.06$ |
|        | 0.1–0.2|        | $-18.53 \pm 0.05$ |          | $-2.27 \pm 0.05$ |
|        | 0.0–0.1| Blue   | $-18.04 \pm 0.16$ | $1.25 \pm 0.10$ | $-2.48 \pm 0.09$ |
|        | 0.1–0.2|        | $-18.71 \pm 0.08$ |          | $-2.82 \pm 0.08$ |
|        | 0.0–0.1| Red    | $-18.28 \pm 0.18$ | $0.97 \pm 0.14$ | $-2.56 \pm 0.09$ |
|        | 0.1–0.2|        | $-18.36 \pm 0.06$ |          | $-2.37 \pm 0.06$ |

Note.—$\phi_*$ is in units of Mpc$^{-3}$. $\sim$ $0.15$ is also plotted for comparison (converted to the AB-magnitude system and to our $H_0$ value, but without accounting for the difference in bandpasses). We refer to Paper I for a discussion on the discrepancy between the FOCA and GALEX LFs. As observed at optical wavelengths (Madgwick et al. 2002; Nakamura et al. 2003), the local LFs of the bluest galaxies tend to have steeper faint-end slopes and fainter characteristic magnitudes $M_*$ than the redder subsamples (although our definition of red would qualify as blue in optically selected samples). The fact that the latest types are observed to fainter absolute magnitudes than the earlier types induces a small bias in the estimate of the faint-end slope of the full sample. The dotted lines in the upper panels of Figure 3 show that the sum of the blue and red LFs is slightly steeper at the faint end than estimated for the galaxy population as a whole, because of the shortage of red galaxies in the faintest bins.

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The present results are consistent with the FUV analysis of a much deeper GALEX field probing adjacent and higher redshifts (Arnouts et al. 2005; Schiminovich et al. 2005). They are also in rough agreement with the rate of evolution derived...
from a photometric-redshift study of GALEX/SDSS data at low $z$ (Budavári et al. 2005), although our FUV LF in the range 0.1 $\leq z \leq 0.2$ seems brighter than the photo-$z$ estimate at overlapping $z$. Both analyses agree very well in the NUV, however (we postpone attempts at explanations for the FUV discrepancy until more comparable data sets are available). We note that evolution seems to be limited by the observed galaxy number counts, especially in the FUV band (Xu et al. 2005), so that the rate of evolution detected at $z \leq 1$ in the GALEX data is expected to slow down. This appears to be the case, based on a photometric-redshift analysis of the Hubble Deep Field–North and South probing 1.75 $\leq z \leq 3.4$ (Arnouts et al. 2005).

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