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

MARIE TREYER1,2, TED K. WYDER1, DAVID SCHIMINOVICH1, STÉPHANE ARNOTTS2, TAMÁS BUDAVÁRI4, BRUNO MILLIARD2, TOM A. BARLOW1, LUCIANA BLANCHI1, YONG-IK BYUN1, JOSÉ DONAS2, KARL FORSTER1, PETER G. FRIEDMAN1, TIMOTHY M. HECKMAN1, PATRICK N. JELINSKY1, YOUNG-WOOK LEE1, BARRY F. MADORE6, ROGER F. MALINA5, D. CHRISTOPHER MARTIN1, PATRICK MORRISSEY1, SUSAN G. NEFF1, R. MICHAEL RICH3, OSWALD H. W. SIEGMUND1, TODD SMALL1, ALEX S. SZALAY1, AND BARRY Y. WELSH7

1 California Institute of Technology, MC 405-47, 1200 East California Boulevard, Pasadena, CA 91125; treyer@srl.caltech.edu
2 Laboratoire d’Astrophysique de Marseille, BP 8, Traverse du Siphon, 13376 Marseille Cedex 12, France
3 Center for Space Astrophysics, Yonsei University, Seoul 120-749, Korea
4 Department of Physics and Astronomy, The Johns Hopkins University, Homewood Campus, Baltimore, MD 21218
5 Space Sciences Laboratory, University of California at Berkeley, 601 Campbell Hall, Berkeley, CA 94720
6 Observatories of the Carnegie Institution of Washington, 813 Santa Barbara St., Pasadena, CA 91101
7 Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771
8 Department of Physics and Astronomy, University of California, Los Angeles, CA 90095

ABSTRACT

We present measurements of the FUV (1530 Å) and NUV (2310 Å) galaxy luminosity functions (LF) at low redshift (z ≤ 0.2) from GALEX observations matched to the 2dF Galaxy Redshift Survey. We split our FUV and NUV samples into two UV−b_j 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_0 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 magnitude brightening between z ~ 0 and 0.13, in agreement with the first analysis of deeper GALEX fields probing adjacent and higher redshifts.

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

1. INTRODUCTION

The importance of estimating luminosity functions (LF) 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 non trivial 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 paper, we use data from the GALEX All-Sky Imaging Survey matched to spectroscopic data from the 2dF Galaxy Redshift Survey 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 to probe evolution at recent epochs (Loveay 2004), and none so far at UV wavelengths. This work is a companion paper to Wyder et al. (2004) who present the total LFs of FUV and NUV selected galaxies in the local (z ≤ 0.1) Universe (hereafter Paper I). It also complements the work of Arnouts et al. (2004), Schiminovich et al. (2004) and Budavár et al. (2004) who quantify the evolution of the UV LF at higher redshift using the GALEX Medium and Deep Imaging Surveys.

The data are summarized in Section 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 Section 4. We assumed a flat ΛCDM cosmology with H_0 = 70 km s⁻¹ Mpc⁻¹, Ω_M = 0.3 and Ω_Λ = 0.7.

2. DATA

The GALEX field-of-view has a diameter of 1.2° and each pointing is imaged simultaneously in both the FUV and NUV bands with effective wavelengths of 1530 Å and 2310 Å, respectively. The GALEX instruments and mission are described by Morissey et al. (2004) and Martin et al. (2001). 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 2dF Galaxy Redshift Survey (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 sam-
ple to areas with effective exposure times \( t_{\text{eff}} > 60\text{ sec} \), and removed sources with magnitude errors greater than 0.4 or contaminated by artifacts from bright stars. We also removed overlap regions by restricting the coverage to the inner 0.45\(^\circ\) of each field. Finally, we excluded GALEX sources where the 2dF redshift completeness was less than 80% as well as areas of the sky excluded from the GALEX-2dF overlap is 56.73 deg\(^2\) in both bands.

We applied a faint magnitude limit of 20 in both bands corresponding to the bluest \( U - b_j \) color observed and beyond which the redshift completeness begins to drop. (N.B.: \( b_j \) 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 AGN/QSO’s). 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 \((FUV - NUV \text{ vs } FUV - b_j)\) for the FUV and NUV selected samples (left and right panel, respectively). Typical error bars are shown in the upper left corners. The thin lines are a set of models by Bruzual & Charlot (2003) covering a range of star-formation histories, ages, metallicities and extinctions. The thick dashed lines are dust free models by Poggianti (1997), from Elliptical to Starburst.

Fig. 1.— Color-color diagrams: \( FUV - NUV \text{ vs } FUV - b_j \) for the FUV (left panel) and the NUV (right panel) selected samples respectively. The thin solid lines are a set of models by Bruzual & Charlot (2003) covering a range of star-formation histories, ages, metallicities and extinctions. The thick dashed lines are dust free models by Poggianti (1997), from Elliptical to Starburst.
passes and derive a spectral index for each galaxy ($\beta = \frac{(F_{\text{FUV}} - F_{\text{NUV}})}{0.425}$, 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. (2004) found that local NUV selected galaxies tend to have lower attenuations than starbursts for a given slope. As our two samples exhibit slopes corresponding 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: $(F_{\text{FUV}} - b_j)_0 \leq z \leq 2$ (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. (2004) using the SDSS star/galaxy separation criteria in overlap regions. It is roughly constant over the range $17 < UV < 20$ in both bands, with mean values of $\sim 79\%$ in the NUV and 92 $\%$ in the FUV (cf Fig. 1 in Paper I). We computed binned luminosity functions using the traditional $V_{\text{max}}$ estimator (Bottinelli 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 Fig. 3 and the best-fit Schechter function parameters are listed in Table 1. The FOCA 2000A LF (Sullivan et al. 2000) at a mean redshift $\bar{z} \sim 0.15$ 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 $M_\ast$ than the reddest 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 Fig. 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, due to the shortage of red galaxies in the faintest bins.

The total FUV and NUV LFs in the highest redshift bin (lower panels in Fig. 3) are both consistent with $\sim 0.3$ magnitude brightening in $M_\ast$ 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 $\langle V/V_{\text{max}} \rangle$ distribution of both $z$-unlimited samples (with $\langle V/V_{\text{max}} \rangle = 0.54$ in both bands instead of the 0.5 expected from a non-evolving 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 (LSBG), 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 6% only 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 underway 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. 2004, Schiminovich et al. 2004). 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. 2004), 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 analysis agree very well in the NUV however (we postpone attempts at explanations for the FUV discrepancy until more comparable datasets are available). We note that evolution seems to be limited by the observed galaxy number counts, especially in the FUV band (Xu et al. 2004), 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-

<table>
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<th>Band</th>
<th>$z$</th>
<th>Type</th>
<th>$M_\ast$</th>
<th>$-\alpha$</th>
<th>$\log \phi_\ast$</th>
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<td>0.0-0.1</td>
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redshift analysis of the HDF North and South probing $1.75 \leq z \leq 3.4$ (Arnouts et al. 2004).

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REFERENCES


Fig. 3.—Top panels: The FUV and NUV LFs at $z \leq 0.1$ (left and right panel, respectively). The blue and red lines (and associated filled circles and asterisks) represent the blue and red subsamples respectively. The black solid lines (and associated empty circles) show the LFs of the full samples (Paper I), while the dotted lines are the sum of the blue and red Schechter functions. The green dotted line is the FOCA 2000Å LF at $z \sim 0.15$ (Sullivan et al. 2000). Bottom panels: The FUV and NUV LFs at $0.1 \leq z \leq 0.2$. Same symbols and lines as above.
Sullivan, M., Treyer, M. A., Ellis, R. S., Bridges, T., Milliard, B.,
Sullivan, M., Treyer, M. A., Ellis, R. S., Mobasher, B. 2004,
MNRAS, 350, 21

Treyer, M. A., Ellis, R. S., Milliard, B., Donas, J., Bridges, T. J.