# Number Counts of GALEX Sources in FUV (1530Å) and NUV (2310Å) Bands

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## ABSTRACT

Number Counts of galaxies in two GALEX bands (FUV: 1530Å and NUV: 2310Å, both in AB magnitudes) are reported. They provide for the first time in the literature homogeneously calibrated number counts of UV galaxies covering continuously a very wide range of UV magnitude (14 – 23.8). Both the FUV and NUV counts are inconsistent with a non-evolution model, while they are in good agreement with evolution models (essentially luminosity evolution) derived from the high-z UV luminosity functions of Arnouts et al. (2004). It is found that the contribution from galaxies detected by GALEX to the UV background is 0.68±0.10 nW $m^{-2}$ $sr^{-1}$ at 1530Å and 0.99±0.15 nW $m^{-2}$ $sr^{-1}$ at 2310Å.

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These are 66±9% and 44±6% of the total contributions of galaxies to the the UV background at 1530Å (1.03±0.15 nW $m^{-2}$ $sr^{-1}$) and at 2310Å (2.25±0.32 nW $m^{-2}$ $sr^{-1}$), respectively, as estimated using the evolution models. Galaxy counts and star counts in 7 regions, each contains a few $deg^2$ GALEX coverage in an area of up to $\sim 30$ $deg^2$, are compared with each other to study the region-by-region variance. This shows that for the galaxy counts the cosmic variance is comparable to the net error due to other uncertainties. The star counts increase with decreasing absolute Galactic latitude |b|.

*Subject headings:* ultraviolet: galaxies – galaxies: active – galaxies: evolution – galaxies: photometry – galaxies: stellar content – stars: formation

## 1. Introduction

The number counts of UV galaxies as a function of the UV magnitude provide direct measures of the density and the evolution of star forming galaxies. They also give strong constraints on the brightness of the cosmic UV background. In the literature, the UV number counts have only been measured in a few small sky areas and in some discontinued UV magnitude ranges by several inhomogeneously calibrated UV surveys (Milliard et al. 1992; Deharveng et al. 1994; Gardner et al. 2000; Sasseen et al. 2002; Iglesias-Páramo et al. 2004). The Galaxy Evolution Explorer (GALEX) has opened a new era of extra-galactic UV astronomy. It is surveying the UV sky with unprecedented efficiency and very high sensitivity. With a pyramid-like survey structure (Martin et al 2004), GALEX presents a uniform and complete picture of galaxy evolution in the UV domain since z$\sim$ 1. In this paper, we carried out galaxy number counts in the two GALEX bands: the FUV (1530Å) and the NUV (2310Å). We have the following science goals: (1) constraining the evolution models of UV galaxies; (2) evaluating the cosmic variance of UV galaxies; (3) estimating the contribution from galaxies to the cosmic background radiation in the two UV bands; (4) providing the calibrations for the UV luminosity functions.

## 2. Data

Three data sets taken from the GALEX database were analyzed in this work, yielding 17174 FUV galaxies and 41512 NUV galaxies in the final samples for the counts (Table 1). All the magnitudes are in the AB system. The calibrations (IR0.2 calibration) have errors of $\sim$ 10% for both FUV and NUV (Morrissey et al. 2004). All of the magnitudes are corrected for the Galactic extinction using the Schlegel et al. (1998) reddening map and the Galactic extinction curve of Cardelli et al. (1989).

The main data set includes 36 Medium-depth Survey (MIS) fields taken from the GALEX internal data release IR0.2. The exposure time of these fields is in the range of 1000 – 1700 seconds with the median of $\sim$ 1500 seconds. They all have full coverage in the Sloan Digitized Sky Survey (SDSS hereafter) DR1 database (Abazajian et al. 2003). In order to minimize the artifacts which concentrate near the periphery of the field of view (Morrissey et al. 2004), we include only sources within 0.45 deg radius from the field center, corresponding to a sky coverage of 0.64 $deg^2$ for each field. The source lists are products of the GALEX pipeline, which uses a combination of the programs SExtractor (Bertin & Arnouts 1996) and Poissonbg, a new program written for GALEX data, to detect and obtain photometry for sources in GALEX images. Poissonbg determines a background map for each GALEX image with a method very similar to that used in SExtractor itself except that the background is estimated using the mean and counts due to sources are iteratively clipped out using the full Poisson distribution, rather than assuming Gaussian statistics which is not appropriate for low counts rate found commonly in GALEX images. Poissonbg also creates a detection threshold map for a user-specified probability using the background image and the full Poisson distribution. The original image is divided by the detection threshold map and given as the detection image to SExtractor while the SExtractor measurements are done on the background-subtracted image. The GALEX magnitude is taken from the $MAG_{AUTO}$ of the SExtractor. Key SExtractor/Poissonbg parameters used by the Pipeline are listed in Table A1 (electronic table). The second data set contains 3 Deep Survey (DIS) fields ($T_{exp}$ =25536s, 23591s, 5607s), all in the Spitzer First Look Survey (FLS) area. These fields are also covered by SDSS DR1. In these DIS fields the source confusion becomes significant. Hence fine tunings in the SExtractor/Poissonbg parameters have been applied (see electronic Table A2). A slight dimming (on the order of 0.1 – 0.2 mag) of the fluxes at magnitudes fainter than 23 was found in the later stage of data analysis, resulting from a small ($\sim$ 2.5%) positive bias of our present sky background estimator. This was corrected empirically according to results of the artificial source simulations (see Section 3). The minimum distance among the 3 DIS fields is 0.86 deg. In order to avoid source duplication, sources were included only when they are within 0.43 deg radius from the field center, corresponding to a coverage of 0.58 $deg^2$ per DIS field. The third data set consists of 95 bright GALEX galaxies (NUV $<$ 16) selected by Buat et al. (2004) in the study of the FIR emission of UV galaxies. The characterization of these galaxies can be found in Buat et al. (2004).

Matches with the SDSS catalogs were carried out for the MIS and DIS sources with a search radius of $4''$. Less than 3% of FUV and NUV sources brighter than 22.5 mag (extinction corrected) have no SDSS counterparts. These are predominantly spurious sources due to artifacts such as pieces of shredded bright extended sources. However, optical counterparts of $r > 22$ of fainter GALEX sources may be missed by SDSS. In the magnitude range of 22.5 and 23.8, about 10% and 20% of FUV and NUV sources do not have SDSS counterparts, respectively. Detailed inspections of the GALEX images showed that most of these sources are real. The SDSS star/galaxy classifications were adopted for MIS/DIS sources with SDSS counterparts. Sources brighter than 22.5 mag and without SDSS counterparts are deemed spurious and dropped off from the sample. Sources with UV magnitudes in the range of 22.5 and 23.8 mag and without SDSS counterparts were included as galaxies.

## 3. Bias Corrections

**Incompleteness**: We adopt the Monte Carlo simulation algorithm developed by Smail et al. (1995) in assessing the incompleteness of GALEX catalogs. Artificial sources of a given UV magnitude were added randomly to a GALEX image. Then the same source extractor which produced the original catalog from the same image was applied and the results were checked for non-detections of the added sources. This gives an estimate of the incompleteness. In order to reproduce the real point spread function (PSF) and the photon noise, the artificial sources were created by dimming the bright sources extracted from the same image, and the photon counts in the region where an artificial source is added were randomized according to the Poisson probability function. The counts in each field were truncated at the magnitude where the incompleteness is becoming larger than 20%. In magnitude bins brighter than the completeness cut-off, the error due to the incompleteness correction is estimated conservatively to be 50% of the correction.

**Spurious Sources**: The spurious source fraction as function of the non-dereddened apparent magnitude was estimated by counting single-detection sources in regions with multipule coverages ('repeatability' method). The effect of incompleteness was accounted for in the analysis. The error is estimated to be 50% of the correction.

**Star/Galaxy Classification Errors and Contamination of AGNs**: The biases due to mis-classifications of sources by SDSS and due to AGN contamination are accessed using the results of photo-z processing of GALEX sources in the MIS fields. By fitting fluxes in 7 bands (5 SDSS bands plus 2 GALEX bands) with templates of stars, galaxies and AGNs, the photo-z processing makes the best use of the information in the SEDs. Although there are still substantial uncertainties for individual sources, the statistics derived from these results are robust. Galaxy counts in a given magnitude bin were derived using the formula

$$c_{gal} = c_{ext} \times g_{ext} + c_{pnt} \times g_{pnt} = c_{ext} \times g_{gal} \quad (1)$$

where $c_{ext}$ is the number counts of SDSS extended sources, $g_{ext}$ the fraction of galaxies among SDSS extended sources, $c_{pnt}$ the number counts of SDSS point sources, $g_{pnt}$ the fraction of galaxies among these sources, and $g_{gal} = g_{ext} + g_{pnt} \times c_{pnt}/c_{ext}$. Both $g_{ext}$ and $g_{pnt}$ were taken from the photo-z results. A 5% error was assigned to the MIS and DIS counts in all FUV and NUV magnitude bins to take into account the uncertainty due to mis-classifications.

**Errors in Foreground Extinction Correction**: The following errors can occur to the extinction correction: (1) incorrect UV extinction law in average; (2) region-to-region variations in the UV extinction law; (3) insufficient angular resolution of the Schlegel map. Based on results of an extensive test involving large samples of low and high extinction regions, a conservative 10 percent extinction correction error was assigned to the counts.

**Eddington Bias**: The Eddington bias (Eddington 1913) is corrected using the algorithm developed by Hogg & Turner (1998, Eq.(4)), assuming the slope of the counts near the detection limit to be $p = 1$.

## 4. Results

The number counts of galaxies in the FUV and NUV bands (Table 1) cover continuously the magnitude range of 14.0 – 23.8 for FUV and 14.0 – 23.6 for NUV. The error bars include not only Poisson errors, errors due to incompleteness and spurious sources corrections, and errors due to source classifications and extinction correction, but also errors due to cosmic variance calculated using the formulism of Glazebrook et al. (1994), which are in general on the same order of Poisson errors. Note that the cosmic variance might be underestimated by the assumption that individual GALEX fields are independent with each other. In Fig.1 the results are compared with UV counts taken from the literature, and with predictions of evolution models. Both the FUV counts and the NUV counts are slightly lower than the FAUST and FOCA counts (Deharveng et al. 1994; Milliard et al. 1992; Iglesias-Páramo et al. 2004) in bins brighter than 21 mag. This is likely to be due to a calibration difference between GALEX and FAUST/FOCA (see also Wyder et al. 2004). It should also be noted that counts of bright UV galaxies by Deharveng et al. (1994) and Iglesias-Páramo et al. (2004) are biased to higher values by galaxy clusters. The XMM-Newton OM-UVW2 counts (Sasseen et al. 2002) appear to be incomplete in bins fainter than 21 mag, where they decrease with increasing magnitude. The GALEX counts are consistent with the HST counts (Gardner et al. 2000) in the magnitude bins where the two overlap.

Both the FUV and NUV counts are inconsistent with predictions by a non-evolution model, which was constructed using the local luminosity functions in the FUV and NUV

(Wyder et al. 2004). The K-correction was estimated using an SED based on the SB4 class spectrum of Kinney et al. (1996) at $\lambda > 1200$Å, a dropping spectrum (by a factor of $\sim 2$) between 1200 — 1000Å, and a sharp cut-off shortward of 912Å. The SB4 spectrum has $\beta = -0.8$. This is close to the value calculated from the ratio of the FUV and NUV luminosity densities in the local universe by Wyder et al. (2004), after allowing for the difference in the calibration zero points (0.03 mag for FUV and -0.10 mag for NUV, Morrissey et al. 2004) used in these two works. The high redshift UV luminosity functions of Arnouts et al. (2004), which indicate a UV luminosity density evolution of $(1+z)^{2.5\pm0.7}$ to $z \sim 1$ (Schiminovich et al. 2004), can be best fitted by an analytic model with $\mathrm{L}_* \propto (1+z)^{2.5}$, $\phi_* \propto (1+z)^{-1.3}$ and $\alpha \propto (1+z)^{-1.3}$. In the expression for the integrated luminosity density of different redshift, $\rho_{\mathrm{L}}(\mathrm{z}) = \phi_*(\mathrm{z})\mathrm{L}_*(\mathrm{z})\Gamma(2-\alpha(\mathrm{z}))$, the evolution of $\phi_*$ and that of $\alpha$ cancel with each other for $0 < \alpha < 2$, leading to $\rho_{\mathrm{L}}(\mathrm{z}) \sim \mathrm{L}_*(\mathrm{z})$. Therefore this is essentially a luminosity evolution model. Predictions by two models, both assuming the same evolution parameters as given above but using different UV SEDs, are plotted in Fig.1: Model I assumes the same SED as that of the no evolution model, and the SED assumed in Model II is otherwise the same except for a flat spectrum between 1200 — 1000Å. These two models should embrace the uncertainties in the SED of wavelengths shorter than the Ly$\alpha$ due both to the Ly$\alpha$ absorption and dust extinction (e.g. Buat et al. 2002), which affects significantly the K-corrections in GALEX bands. In the bins covered by the GALEX counts, the two evolution models give almost identical results, both fit the data very well. In fainter bins, the two models show significant difference in the FUV band due to different K-corrections. Both models fit the HST NUV counts well, given the substantial uncertainties of the data, but are slightly lower than the HST FUV counts.

Using the mean of the integral counts predicted by Model I and Model II, and the beam size of the DIS FUV maps (FWHM=5.4″) and that of DIS NUV maps (5.6″), we estimate that the 40-beam-per-source confusion limits of the FUV and NUV maps are FUV=25.3 and NUV=24.0, respectively. The major contribution to the incompleteness at the boundary of the NUV counts (NUV=23.6) is from the source confusion, indicating the NUV counts being confusion limited. The confusion limit of the DIS FUV maps, on the other hand, is significantly deeper than the last bin of the FUV counts. The contribution from galaxies detected by GALEX to the UV background is 0.68±0.10 nW m$^{-2}$ sr$^{-1}$ at 1530Å and 0.99±0.15 nW m$^{-2}$ sr$^{-1}$ at 2310Å. Extrapolating the counts using the above two evolution models and integrating down to flux=0, the total extragalactic UV background due to galaxies is 1.03±0.15 nW m$^{-2}$ sr$^{-1}$ at 1530Å and 2.25±0.32 nW m$^{-2}$ sr$^{-1}$ at 2310Å, respectively. The errors include both model uncertainties and GALEX calibration uncertainties. Our results are significantly lower than the results of Gardner et al. (2000) who found that the contributions from resolved sources to the UV background are $3.9^{+1.1}_{-0.8}$ nW m$^{-2}$ sr$^{-1}$ and

$3.6^{+0.7}_{-0.5}$ nW m$^{-2}$ sr$^{-1}$ at 1595Å and 2365Å, respectively. Our results are in good agreement with that of Armand et al. (1994), who found that the contribution from galaxies to the UV background at 2000Å is 40 – 140 photons cm$^{-2}$ $s^{-1}$ Å$^{-1}$ sr$^{-1}$, corresponding to 0.80 – 2.78 nW m$^{-2}$ sr$^{-1}$.

In Fig.2 FUV and NUV number counts of galaxies and stars in 7 regions with MIS and DIS coverage are presented in 4 panels. For galaxy counts the error bars do not include the cosmic variance in these plots. It appears that differences between galaxy counts in different regions are consistent with the error bars, indicating that the cosmic variance is not very significant for UV surveys covering more than a few square degrees. The counts of stars show a significant trend in the sense that the less the absolute Galactic latitude (|b|), the higher the counts. The NUV counts of stars are rather flat, higher than galaxy counts in bins brighter than $\sim 21$ mag. The FUV counts of stars are lower than the counts of galaxies in bins fainter than $\sim 18$ mag. These data are compared with predictions of a star counts model. The model closely follows the Bahcall-Soneira model (Bahcall 1986) with an updated parameterization of the Galactic spheroid from Gould et al. (1998). The stellar luminosity function of Wielen et al. (1983) is used. An additional disk white dwarfs population (scale height of 275 kpc) is included, with a luminosity function drawn from Liebert et al. (1988). The model generally reproduces the trends of the observed star counts, though the predicted counts in both bands are slightly flatter than the observations.

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Table 1. FUV and NUV Number Counts of Galaxies

| FUV mag | counts $deg^{-2}mag^{-1}$ | f[a] | $g_{gal}$ | N | area $deg^2$ | NUV mag | counts $deg^{-2}mag^{-1}$ | f[a] | $g_{gal}$ | N | area $deg^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 14.2 | 0.008 ± 0.008 | 1.00 | 1.00 | 2 | 615.00 | 14.2 | 0.020 ± 0.015 | 1.00 | 1.00 | 5 | 615.00 |
| 14.6 | 0.029 ± 0.018 | 1.00 | 1.00 | 7 | 615.00 | 14.6 | 0.016 ± 0.012 | 1.00 | 1.00 | 4 | 615.00 |

Note. — Table 1 is published in its entirety in the electronic edition of The Astrophysical Journal Letters. A portion is shown here for guidance regarding its form and content.

[a] $f = (1 - f_{spur})/(1 - f_{incomp})$, where $f_{spur}$ is the correction for the spurious sources, and $f_{incomp}$ the correction for the incompleteness.

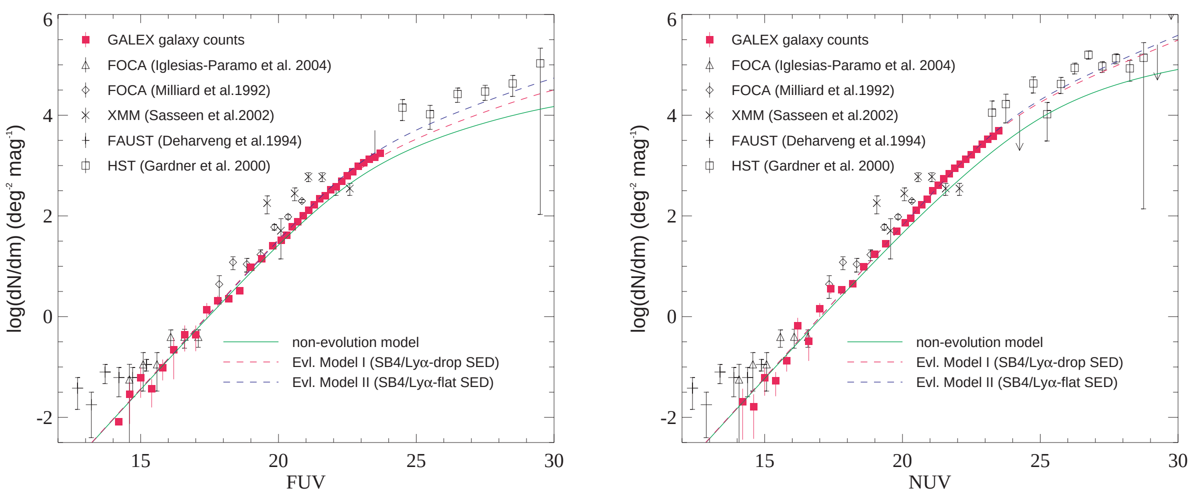


Fig. 1.— **Left**: FUV (1530Å) number counts of galaxies. **Right**: NUV (2310Å) number counts of galaxies. Number counts in other UV bands are converted to counts in the GALEX bands according to an assumed UV slope of $\beta = -0.8$.

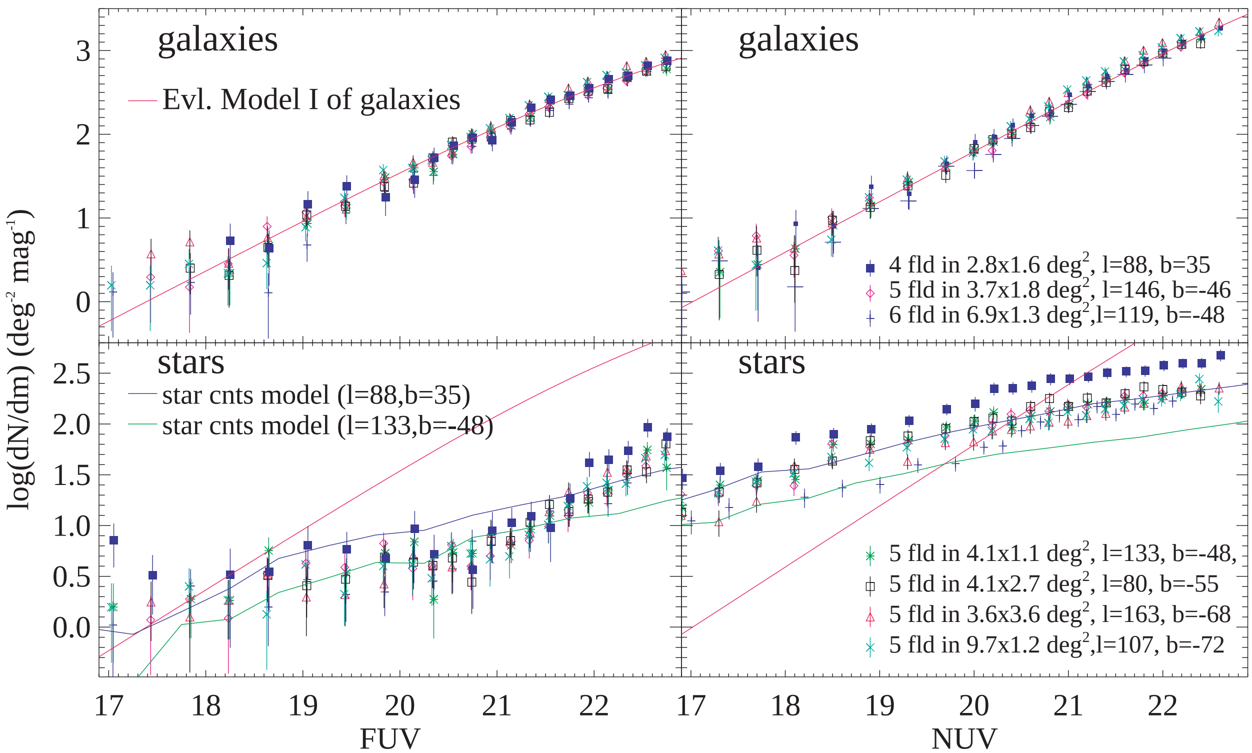


Fig. 2.— FUV and NUV number counts of galaxies and stars in 7 regions with MIS and DIS coverage.