NUMBER COUNTS OF GALEX SOURCES IN FAR-ULTRAVIOLET (1530 Å) AND NEAR-ULTRAVIOLET (2310 Å) BANDS

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ABSTRACT

Number counts of galaxies in two Galaxy Evolution Explorer (GALEX) bands [far-UV (FUV: 1530 Å) and near-UV (NUV: 2310 Å); both in AB magnitudes] are reported. They provide for the first time in the literature homogeneously calibrated number counts of UV galaxies continuously covering a very wide range in the UV magnitude (14–23.8). Both the FUV and NUV counts are inconsistent with a nonevolution model, whereas they are in good agreement with evolution models (essentially luminosity evolution) derived from the high-z UV luminosity functions of Arnouts et al. We find that the contribution from GALEX-detected galaxies to the UV background is 0.68 ± 0.10 nW m−2 sr−1 at 1530 Å and 0.99 ± 0.15 nW m−2 sr−1 at 2310 Å. These are 66% ± 9% and 44% ± 6% of the total contributions of galaxies to the UV background at 1530 Å (1.03 ± 0.15 nW m−2 sr−1) and at 2310 Å (2.25 ± 0.32 nW m−2 sr−1), respectively, as estimated using the evolution models. Galaxy counts and star counts in seven regions, each containing a few square degrees of sky area 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. 2000; Sasseen et al. 2002; Iglesias-Páramo et al. 2004). The Galaxy Evolution Explorer (GALEX) has opened a new era of extragalactic UV astronomy. It is surveying the UV sky with unprecedented efficiency and very high sensitivity. With a pyramid-like survey structure (Martin et al. 2005), GALEX presents a uniform and complete picture of galaxy evolution in the UV domain since z ∼ 1. In this Letter, we present galaxy number counts carried out in the two GALEX bands: the far-UV (FUV: 1530 Å) and the near-UV (NUV: 2310 Å). 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, and (4) providing the calibrations for the UV luminosity functions.

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. 2000; Sasseen et al. 2002; Iglesias-Páramo et al. 2004). The Galaxy Evolution Explorer (GALEX) has opened a new era of extragalactic UV astronomy. It is surveying the UV sky with unprecedented efficiency and very high sensitivity. With a pyramid-like survey structure (Martin et al. 2005), GALEX presents a uniform and complete picture of galaxy evolution in the UV domain since z ∼ 1. In this Letter, we present galaxy number counts carried out in the two GALEX bands: the far-UV (FUV: 1530 Å) and the near-UV (NUV: 2310 Å). 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, and (4) providing the calibrations for the UV luminosity functions.

2. DATA

Three data sets taken from the GALEX database are analyzed in this work, yielding 17,174 FUV galaxies and 41,512 NUV galaxies in the final samples for the counts (Table 1). All the magnitudes are in the AB system. The calibrations (IR.0.2 calibration) have errors of ∼10% for both FUV and NUV (Morrissey et al. 2005). All of the magnitudes are corrected for 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 Imaging Survey (MIS) fields taken from the GALEX internal data release 0.2 (IR.0.2). The exposure time of these fields is in the range of 1000–1700 s, with a median of ∼1500 s. They all have full coverage in the Sloan Digitized Sky Survey First Data Release (SDSS DR1) database (Abazajian et al. 2003). In order to minimize the artifacts that concentrate near the periphery of the field of view (Morrissey et al. 2005), we include only sources within a 0.755 radius of the field center, corresponding to a sky coverage of 0.64 deg2 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 using a method very similar to that used in SExtractor itself, except that the background is estimated using the mean and counts due to sources that are iteratively clipped out using the full Poisson distribution, rather than assuming Gaussian statistics, which is not appropriate for the low counts rate commonly found 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 MAG_AUTO of SExtractor. Key SExtractor/POISSONBG parameters used by the pipeline are listed in Table 1 (second section of online version). The second data set contains three Deep Imaging Survey (DIS) fields (Texp = 25,536, 23,591, and 5607 s), all in the Spitzer First Look Survey 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 third section of Table 1). 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 (∼2.5%) positive bias of our present sky background estimator. This was corrected empirically, according to results of the artificial source simulations (see §3). The minimum distance among the three DIS fields is 0.086. In order to avoid source duplication, sources were included only when they are within 0.43 radius from the field center, corresponding to a coverage of 0.58 deg² per DIS field. The third data set consists of 95 bright GALEX galaxies (NUV < 16) selected by Buat et al. (2005) in the study of the far-IR emission of UV galaxies. The characterization of these galaxies can be found in Buat et al. (2005).

Matches with the SDSS catalogs were carried out for the MIS and DIS sources using 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 have been missed by SDSS. In the magnitude range of 22.5 to 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 from the sample. Sources with UV magnitudes in the range of 22.5 to 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 the GALEX catalogs. Artificial sources of a given UV magnitude were added randomly to a GALEX image. Then the same source extractor that produced the original catalog from the same image was applied, and the results were checked for nondetections of the added sources. This gives an estimate of the incompleteness. In order to reproduce the real point-spread function 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 becomes larger than 20%. In magnitude bins brighter than the completeness cutoff, the error due to the incompleteness correction is estimated conservatively to be 50% of the correction.

Spurious sources.—The fraction of spurious sources as a function of the nonreddened apparent magnitude was estimated by counting single-detection sources in regions with multiple 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 active galactic nuclei.—The biases due to misclassifications of sources by SDSS and due to active galactic nucleus (AGN) contamination are assessed using the results of photo-z processing of GALEX sources in the MIS fields. By fitting fluxes in seven bands (five SDSS bands plus two GALEX bands) with templates of stars, galaxies, and AGNs, the photo-z processing makes the best use of the information in the spectral energy distributions (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

$$c_{\text{gal}} = c_{\text{ext}} g_{\text{ext}} + c_{\text{pnt}} g_{\text{pnt}} = c_{\text{ext}} g_{\text{gal}}$$

where $c_{\text{ext}}$ is the number counts of SDSS extended sources, $g_{\text{ext}}$ is the fraction of galaxies among SDSS extended sources, $c_{\text{pnt}}$ is the number counts of SDSS point sources, $g_{\text{pnt}}$ is the fraction of galaxies among these sources, and $g_{\text{gal}} = g_{\text{ext}} + g_{\text{pnt}} c_{\text{pnt}} / c_{\text{ext}}$. Both $g_{\text{ext}}$ and $g_{\text{pnt}}$ 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 misclassifications.

Errors in foreground extinction correction.—The following errors can occur to the extinction correction: (1) incorrect UV extinction law on average, (2) region-to-region variations in the UV extinction law, and (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% extinction correction error was assigned to the counts.

Eddington bias.—The Eddington bias (Eddington 1913) is corrected using the algorithm developed by Hogg & Turner.

| FUV (mag) | Counts (deg⁻² mag⁻¹) | $f^*$ | $g_{\text{ext}}$ | Area (deg²) | NUV (mag) | Counts (deg⁻² mag⁻¹) | $f^*$ | $g_{\text{ext}}$ | Area (deg²) |
|-----------|-----------------------|-------|------------------|-------------|-----------|-----------------------|-------|------------------|-------------|
| 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 | 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.

$f = (1 - f_{\text{spur}})(1 - f_{\text{incomp}})$, where $f_{\text{spur}}$ is the correction for the spurious sources, and $f_{\text{incomp}}$ the correction for the incompleteness.
(1998, eq. [4]), assuming the slope of the counts near the detection limit to be $\beta = -0.8$.

4. RESULTS

The number counts of galaxies in the FUV and NUV bands (Table 1) continuously cover 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 source corrections, and errors due to source classifications and extinction correction, but also errors due to cosmic variance calculated using the formalism of Glazebrook et al. (1994), which are in general on the same order as Poisson errors. Note that the cosmic variance might be underestimated by the assumption that individual GALEX fields are independent of each other. In Figure 1 the results are compared with UV counts taken from the literature, and with predictions of evolution models. Both the FUV and 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 the result of a calibration difference between GALEX and FAUST/FOCA (see also Wyder et al. 2005). 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 Optical Monitor UVW2 filter 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 Hubble Space Telescope (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 nonevolution model, that was constructed using the local luminosity functions in the FUV and NUV (Wyder et al. 2005). The $K$-correction was estimated using an SED based on the SB4 class spectrum of Kinney et al. (1996) at $\lambda > 1200$ Å, a drop in spectrum (by a factor of $\sim 2$) between 1200–1000 Å, and a sharp cutoff shortward of 912 Å. The SB4 spectrum has $\beta = -0.8$. This is close to the value calculated by Wyder et al. (2005) from the ratio of the FUV and NUV luminosity densities in the local universe, after allowing for the difference in the calibration zero points (0.03 mag for FUV and $-0.10$ mag for NUV; Morrissey et al. 2005) used in these two works. The high-redshift UV luminosity functions of Arnouts et al. (2005), which indicate a UV luminosity density evolution of $(1+z)^{2.5\pm0.7}$ to $z \sim 1$ (Schiminovich et al. 2005), can be best fitted by an analytic model with $L_p \propto (1+z)^{2.5}$, $\phi_p \propto (1+z)^{-1.3}$, and $\alpha \propto (1+z)^{-1.3}$. In the expression for the integrated luminosity density of different redshifts, $\int L_p(z) \phi(z) d\phi(z)$, the evolution of $\phi$ and of $\alpha$ cancel each other out, leading to $\phi(z) \sim L_p(z)$. 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 Figure 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 and 1000 Å. These two models should embrace the uncertainties in the SED of wavelengths shorter than the Ly$\alpha$, because of both the Ly$\alpha$ absorption and dust extinction (e.g., Buat et al. 2002), which significantly affects 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 a significant difference in the FUV band, because of 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 ($\text{FWHM} = 5^\prime.4$) and that of the DIS NUV maps ($5^\prime.6$), we estimate that the 40-beam-per-source confusion limits of the FUV and NUV maps are $FUV = 25.3$ and $NUV = 24.0$. 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 are 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 GALEX-detected galaxies to the UV background is $0.68 \pm 0.10$ nW m$^{-2}$ sr$^{-1}$ at 1530 Å and $0.99 \pm 0.15$ nW m$^{-2}$ sr$^{-1}$ at 2310 Å. Extrapolating the counts using the above two evolution models and integrating down to a flux of zero, the total extragalactic UV background due to galaxies is $1.03 \pm$
Fig. 2.—FUV and NUV number counts of galaxies and stars in seven regions covered by MIS and DIS.

0.15 nW m$^{-2}$ sr$^{-1}$ at 1530 Å and 2.25 ± 0.32 nW m$^{-2}$ sr$^{-1}$ at 2310 Å. The errors include both model uncertainties and \textit{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$^{+1.1}_{-0.8}$ and 3.6$^{+0.7}_{-0.5}$ nW m$^{-2}$ sr$^{-1}$ at 1595 and 2365 Å, 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 2000 Å is 40–140 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$, corresponding to 0.80–2.78 nW m$^{-2}$ sr$^{-1}$.

In Figure 2, FUV and NUV number counts of galaxies and stars in seven regions covered by MIS and DIS are presented in four 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 ~21 mag. The FUV counts of stars are lower than the counts of galaxies in bins fainter than ~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 dwarf 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, although the predicted counts in both bands are slightly flatter than the observations.

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