NEW CONSTRAINTS ON GALAXY EVOLUTION FROM THE OPTICAL MONITOR ON XMM-NEWTON

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Abstract

We use galaxies detected in a deep ultraviolet XMM-Newton Optical Monitor image and a model that predicts UV galaxy counts based on local counts and evolution parameters to constrain galaxy evolution to Z=1.2. The 17' square 2000 Å (UVW2 filter) image was taken as part of the XMM-OM team's guaranteed time program. We detect sources in this image to a flux limit of 2.7×10^{-17} ergs cm^{-2} s^{-1} Å^{-1} (AB magnitude = 22). Since some of the sources may be stars, we perform a number of checks, including shape, color and implied distance to remove stars from the detected counts. We find galaxy number counts as a function of magnitude roughly in agreement Milliard et al. (1992), but again find these counts are in excess of evolution models. The excess counts at faint magnitudes may provide evidence for either a new population of galaxies emerging around Z=0.7 or more dramatic evolution than some earlier predictions. The integrated light from the detected galaxies totals 32–36 ph cm^{-2} s^{-1} Å^{-1} sr^{-1}, placing a firm lower limit on the integrated UV light from galaxies.

Key words: galaxies: evolution – ultraviolet: galaxies

1. Introduction

Measurements of the integrated light from a galaxy at 2000 Å provides a fairly direct measure of the instantaneous rate of star formation, since the massive stars that provide most of this radiation are short-lived compared with the age of the galaxy. Knowledge of the star formation rate also gives a measure of the rate of heavy element production in a galaxy, or in the universe when a large sample of galaxies are measured (Madau et al. 1996). The integrated light from these galaxies contributes to the extragalactic background light at ultraviolet wavelengths, whose main sources are hot stars and active galactic nuclei. Measurements of galaxy number counts in the ultraviolet have been made by Milliard et al. (1992) using the FOCA balloon-borne UV telescope, Gardner et al. (2000) and Hill et al. (1997) using HST archival fields. These data have been interpreted with models that predict number counts based on galaxy spectral energy distributions (SED's) and luminosity functions, such as those of Armand & Milliard (1994) and Granato et al. (2000). The total far-ultraviolet extragalactic background has been measured to be as high as 500 ph cm^{-2} s^{-1} Å^{-1} and as low as 30 ph cm^{-2} s^{-1} Å^{-1} (see review by Bowyer 1991). Predictions for the number of galaxies that might be detected in deep ultraviolet Optical Monitor (OM) images are given by Sasseen et al. (1997). In this paper, we detect galaxies in a deep UV image taken with the Optical Monitor (OM) and use these galaxy number counts to place constraints on galaxy luminosity evolution via a a galaxy evolution model similar to that of Armand & Milliard (1994). We also find a lower limit to the galaxy contribution to the extragalactic UV background.

2. The Data

The OM 13 hr deep field (at J2000.0 13 34 37.00, +37 54 44.0) was observed for approximately 200 ks with XMM-Newton around June 22, 2001. Details of the OM exposures used in this study are shown in Table 1.

Table 1. OM images used in this study.

Filter	Central Wavelength (Å)	Exposure Time (ksec)
B	4200	10
U	3900	10
UVW1	3000	20
UVM2	2500	31.5
UVW2	2000	30

Several exposures of typically 7 ks were brought to a common astrometric reference frame and coadded. We searched each image for sources using Sextractor and made a catalog of the sources we found. We concentrate here on sources in the UVW2 image (Fig. 1) and use measurements in the other filters to differentiate between stars, galaxies and QSO's. We also use a deep R band image (to R∼27) of this field taken with the 8m Subaru telescope on Mauna Kea (Fig. 2) to check for source shape and possible confusion. We perform two checks to discrim-

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inate stars from galaxies. First, we compare the SED of each UVW2 source (determined from OM photometry) against stellar templates. Second, we compute an inferred distance, as if the source were a main sequence star, from U-B color and B magnitude, as shown in Fig. 3. We find these checks form reliable stellar discriminators for more than 90% of the sources brighter than AB=22. [1] We also find a number of QSO's in the field that show UV excess and appear point-like in the OM and Subaru images. We categorize these separately in our galaxy number counts. Further work remains to completely discriminate any remaining stellar content and the QSO populations.

We plot the detected galaxy counts as a function of magnitude in Fig. 4. Our counts are in approximate agreement with that of Milliard et al. 1992 (also shown in Fig. 4) in the range of overlap, and we extend these counts to AB=22.

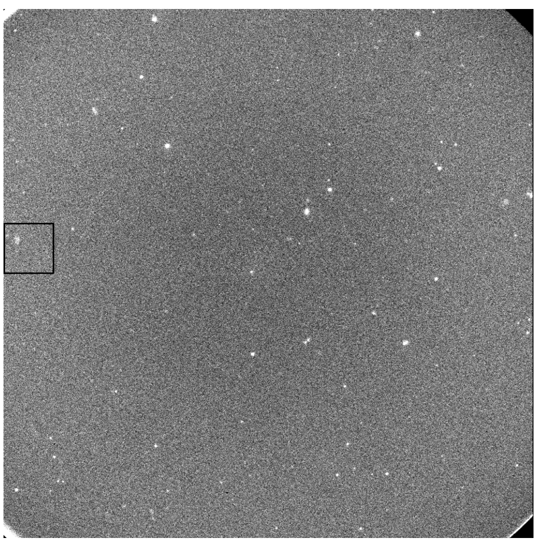

Figure 1. The 17' by 17' UVW2 (2000 A) image of total exposure 31,450 s. The five sigma detection limit determined with 5" FWHM PSF is $3{\times}10^{15}$ ergs $cm^{-2}s^{-1}$. We detected 122 sources above this limit. Source with further detail is indicated in box.

3. The Models

We have constructed a model is similar to that of Armand & Milliard (1994) and use it to predict galaxy counts at

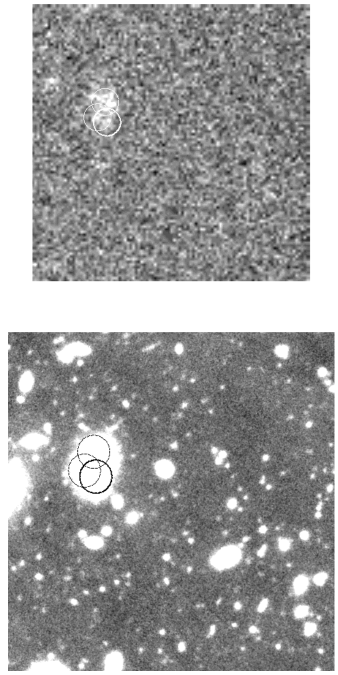

Figure 2. Detail of an example source region in UVW2 image (upper) and Subaru R-band image (lower) with detection limit R∼27. We examine multiple detections in one location in more detail, both in the direct images and in a surface plot using the Subaru image.

2000 Å as a function of apparent magnitude. The model uses a Schechter absolute luminosity distribution function for 6 different galaxy types at redshifts between zero and 1.2, along with K-corrections and a single parameter luminosity evolution factor for each galaxy type. We have normalized the Schechter function using observed counts at Bj=17, and set our evolution parameters to agree with the modeled galactic evolution of Rocca-Volmerange & Guiderdoni (1988), following Armand & Milliard (1994). Our model implicitly includes the effects of dust absorption and scattering because it is based on observed UV SED's. Like Armand & Milliard, our model predicts fewer galaxies in each magnitude band than our measured number counts, as shown in Figure 4. We also compare the observed counts with the model of Granato et al. (2000), whose model explicitly includes expected contributions to the observed galaxy counts from starburst galaxies and dust. Our model agrees well with the Granato et al. model that includes dust, but our observed counts are higher than both models that include dust.

4. Discussion

The summed the flux from non-stellar sources detected in the UVW2 image totals 32–36 ph cm^{-2} s^{-1} sr^{-1} Å^{-1}, with the higher limit including the contribution from QSO's and active galaxies. The integrated far-ultraviolet light

[1] The AB magnitude system is defined by AB $= -2.5log(F_\nu) - 48.6$ where F_ν is given in ergs cm^{-2} s^{-1} Hz^{-1} (Oke 1971).

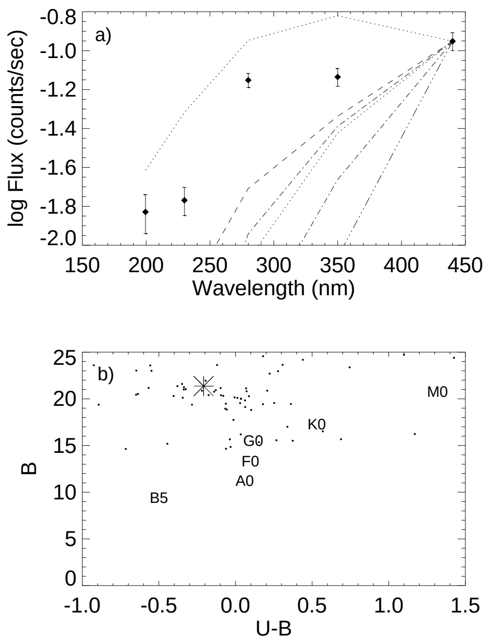

Figure 3. a) The spectral energy distribution of the example source measured with Optical Monitor filter bandpasses (points) plotted with template stellar SED's for B0, A0, F0, G0, K0 and M0 dwarf stars (curves) for comparison. The hot galaxy SED's is evident here and in most cases. b) A distance estimate based on U-B colors if the object were a main-sequence star. In the second plot, the stellar type labels are shown at the position corresponding to where a main sequence star of that stellar type at a distance of 1 kpc would lie. In most cases, these two figures allowed satisfactory discrimination between stars and galaxies. We also referred to a surface plot of the source location extracted from the Subaru image.

from discrete galaxies has been measured recently by Gardner et al. (2000) to be 144–195 ph cm^{-2} s^{-1} sr^{-1} Å^{-1}, based on galaxies detected in the range AB = 24 to 29.5 and a model to infer the flux from brighter galaxies. These authors claim there appears to be a break in the slope of the galaxy number counts that occurs around AB = 24, with substantial flattening of function at fainter magnitudes. Our measurements show an intriguing downturn in galaxy counts at the faint end, which may indicate the start of the change in the slope of the number counts. There still remains some uncertainty in the number counts in the gap between our measurements and those of Gardner et al. (2000), which indicates the total integrated flux of galaxies is still uncertain.

The discrepancy between the models shown in Fig. 4 and both our data and that of Milliard et al. 1992 may indicate that we are missing some components in our understanding of how galaxies evolve. Some possible reasons for the descrepancy between their model and measurements

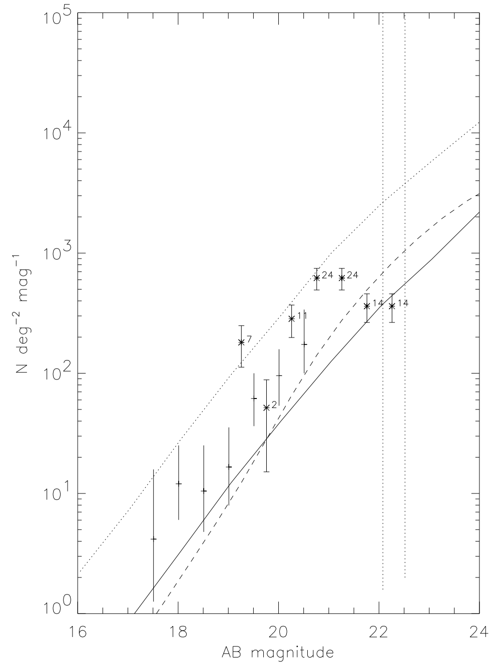

Figure 4. Our measured galaxy counts (starred points) after removing probable stellar sources. The number indicates the number of galaxies in that bin. We also show the data of Armand & Milliard (1994) in a similar bandpass, which are in rough agreement with galaxy counts in this study. We show our model results, as the dotted line. We also show the modeling results of Granato et al. (2000), where the dotted line is the model without dust included, and the solid line includes the effects of dust. The vertical dotted lines indicate the 3-σ and 2-σ detection levels in our UV image.

are given by Armand & Milliard 1994, including faster evolution of the star formation rate or the possiblity that there is a population of blue galaxies that is substantially more numerous at z = 0.7 than they are today.

5. Future Work

There are a number of effects we have not yet evaluated in detail that may affect our measurement and conclusions. These include the effects of galaxy inclination, morphology and apertures on our photometry, the effects of comparing measurements made in slightly different bandpasses, and the detailed effects of dust absorption and possible evolution in galaxies (Vacca 1997). Our simple model assumes a smooth evolution in star formation, but there is evidence that star formation may be espisodic or occur in bursts, possibly because of merger activity, *e.g.* Johnson et al. (1998). Galaxies change over time in many ways and our model predicts only one facet of these changes, namely an evolving star formation rate. The full picture of galaxy evolution is certainly more complicated. It remains to explore further the connections between changes in the star formation rate and changes in galaxy appearance and morphology, metallicity, gas content, spectral energy output, and merger activity that have been discussed at length by other researchers.

6. Conclusions

1) We have obtained galaxy counts at 2000 Å to a magnitude of AB = 22 in deep images from the Optical Monitor on XMM-Newton. The long OM exposure allows us to measure galaxy counts 1.5 magnitudes fainter than Armand & Milliard (1994), and we find similar counts in range of overlap. 2) Two evolutionary models underpredict the observed galaxy counts, and may indicate that several process may be at work, including episodic star formation, changes in the optical depth within galaxies to 2000 Å radiation, or a new population of galaxies that is less visible in the present epoch. 3) The total integrated flux from the galaxies we detect to AB=22 is 32–36 ph cm^{-2} s−1 $Å^{-1}$ sr^{-1}. This flux is a lower limit to the integrated extragalactic background light at 2000 Å, and represents about 20–25% of the integrated, far-ultraviolet flux from galaxies inferred from the deep HST measurements of Gardner et al. 2000.

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