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ABSTRACT

We present the 3 – 8 keV and 8 – 24 keV number counts of active galactic nuclei (AGN) identified in the NuSTAR extragalactic surveys. NuSTAR has now resolved ~35% of the X-ray background in the 8 – 24 keV band, directly identifying AGN with obscuring columns up to ~ 10^25 cm^-2. In the softer 3 – 8 keV band the number counts are in general agreement with those measured by XMM-Newton and Chandra over the flux range 5 × 10^-15 ≤ S(3 – 8keV)/erg s^-1 cm^-2 ≤ 10^-12 probed by NuSTAR. In the hard 8 – 24 keV band NuSTAR probes fluxes over the range 2 × 10^-14 ≤ S(8 – 24 keV)/erg s^-1 cm^-2 ≤ 10^-12, a factor ~100 fainter than previous measurements covering this energy range. The slope of the 8 – 24 keV number counts closely matches predictions from AGN population-synthesis models that account for the shape and intensity of the diffuse cosmic X-ray background. This directly confirms the existence of a population of obscured and/or hard X-ray sources inferred from the shape of the integrated diffuse cosmic X-ray background. The measured NuSTAR counts lie significantly above simple extrapolations of the Swift/BAT 15 – 55 keV number counts measured at higher fluxes (S(15 – 55 keV) ≥ 10^{-13} erg s^{-1} cm^{-2}) for any realistic AGN spectral model. The most natural explanation for the difference is an evolution in the AGN population between the very local objects seen by BAT and the more distant (z ∼ 0.5 – 1) NuSTAR sample that is not accounted for in the current models.

Subject headings: galaxies: active – galaxies: nuclei – galaxies: Seyfert – surveys – X-rays: diffuse background – X-rays: galaxies

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1. INTRODUCTION

A complete census of accreting supermassive black holes (SMBH) throughout cosmic time is necessary to quantify the efficiency of accretion, which is believed to drive the majority of SMBH growth (e.g., Soltan 1982, Yu & Tremaine 2002, Di Matteo et al. 2008, Merloni & Heinz 2008). X-ray emission is nearly universal from the luminous Active Galactic Nuclei (AGN) that signal the most rapid SMBH growth phases. Unlike optical and infrared light, X-rays are not diluted by host-galaxy emission, which is generally weak above ~1 keV. X-rays are also penetrating, and hard (>10 keV) X-rays are visible through columns up to $N_H = 10^{25} \text{cm}^{-2}$. For even higher columns AGN can be identified through scattered X-rays, although the emission becomes progressively weaker with increasing column.

Cosmic X-ray surveys with Chandra and XMM-Newton have provided measurements of the demographics of the AGN population and its evolution in the 0.1 – 10 keV band out to large cosmic distances (see Brandt & Alexander 2015 for a recent review). These surveys are sufficiently complete over a broad enough range of luminosity and redshift that many fundamental questions regarding AGN evolution can be addressed. In the deepest fields, >80% of the 2 – 10 keV Cosmic X-ray Background (CXB) has been resolved into individual objects (Hickox & Markevitch 2006, Brandt & Alexander 2015).

At X-ray energies above 10 keV the observational picture is far less complete. Coded-mask instruments such as INTEGRAL and Swift/BAT have probed the demographics of hard X-ray emitting AGN in the very local universe, to redshifts $z \lesssim 0.1$ (Dullemand et al. 2008, Beckmann et al. 2009). The fraction of the CXB resolved by these instruments at its peak intensity (20 – 30 keV) is ∼1% (Krivonos et al. 2007, Ajello et al. 2012, Vasudevan, Mushotzky & Gandhi 2013). Thus, until now, samples of AGN selected at $>10$ keV, which are inherently less biased by obscuration than those at lower energy, could not be used to probe AGN demographics, and in particular the evolution of highly obscured to Compton-thick (N_H $> \sigma_T^{-1} \sim 10^{24} \text{cm}^{-2}$) sources.

There is, therefore, strong motivation for extending sensitive X-ray surveys to high energy. Simple extrapolations of AGN populations detected by Chandra and XMM-Newton to higher energies based on average spectral properties fail to reproduce the shape and intensity of the CXB at 30 keV (e.g., Gilli, Comastri & Hasinger 2007). This indicates either that spectral models based on the small samples of high-quality 0.1 - 100 keV measurements used in CXB synthesis models fail to capture the true spectral complexity of AGN, or that an additional highly obscured AGN population is present in the redshift range 0 $\lesssim z \lesssim 1$. It is likely that both factors are important at some level. A higher fraction of reflected emission than typically assumed, which hardens the emission above 10 keV, appear to be present in moderately obscured, $25 < \log(N_H/\text{cm}^{-2}) < 24$, AGN (Ricci et al. 2011). Even at moderate redshifts, reflection fractions are difficult to constrain with data restricted to $<10$ keV (e.g., Del Moro et al. 2014). In addition, it is difficult at low redshifts to properly measure high obscuring columns, which can lead to large errors in estimating intrinsic AGN luminosities (e.g., Lansbury et al. 2015). It is also challenging to identify Compton-thick objects in the range 0 $\lesssim z \lesssim 1$ with the limited bandpass of Chandra and XMM-Newton (at $z \gtrsim 2$ these missions sample rest frame energies above 20 keV). Thus both to characterize highly obscured AGN and constrain their evolution at $z \lesssim 1$ requires sensitive surveys at energies above 10 keV.

The Nuclear Spectroscopic Telescope Array (NuSTAR), the first focusing high-energy X-ray (3 - 79 keV) telescope on orbit (Harrison et al. 2013), has been executing a series of extragalactic surveys as part of its core program, with aim of measuring the demographics and properties of obscured AGN. Through contiguous surveys in fields with existing multi-wavelength data combined with dedicated spectroscopic followup of sources serendipitously identified in individual fields, the NuSTAR extragalactic surveys have improved the sensitivity limits in the hard, 8 – 24 keV band by two orders of magnitude relative to INTEGRAL or Swift/BAT, and have probed a wide range in redshift, out to $z \gtrsim 2$.

In this paper we present the X-ray number counts (log N - log S) of AGN, including the first sensitive measurements in the 8 – 24 keV band. We reach fluxes of S(8 – 24 keV) $\sim 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, a factor of 100 deeper than previous measurements in this band. We compare the number counts to predictions from X-ray background synthesis models, and to extrapolations from Chandra and XMM-Newton surveys, and compare the intensity of resolved sources to that of the CXB. A companion paper (Aird et al. 2015a) presents direct constraints on the $>10$ keV AGN X-ray luminosity function. We adopt a flat cosmology with $\Omega_M = 0.7$ and $h = 0.7$, and quote 68.3% (i.e. 1$\sigma$ equivalent) errors unless otherwise noted.

2. OBSERVATIONS AND DATA REDUCTION

For the results in this paper we include all components of the NuSTAR extragalactic survey program that were completed and analyzed prior to March 2015. This includes coverage of well-studied contiguous fields as well as identification and followup of sources serendipitously detected in all NuSTAR fields. Figure 1 shows the area as a function of depth for the survey components included in this work. At the shallow end, NuSTAR surveyed 1.7 deg$^2$ of the Cosmic Evolution Survey field (COSMOS; Scoville et al. 2007) to a depth of $S(8 - 24 \text{ keV}) = 1.3 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. The catalog and results from this survey are presented in Civano et al. (2015) (hereafter C15). At the deep end, NuSTAR surveys have reached depths of $S(8 - 24 \text{ keV}) = 2.5 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ in the Extended Chandra Deep Field South (ECDFS; Lehmer et al. 2005) over an area of 0.3 deg$^2$ and in the deep Chandra region of the Extended Groth Strip (Goulding et al. 2012, Nandra et al. 2015) over an area of 0.23 deg$^2$. The ECDFS source catalog is presented in Mullaney et al. (2015) (hereafter M15) and the EGS catalog will be presented in Aird et al. (in prep). The serendipitous survey adopts a similar approach used with the Chandra SEXSI survey (Harrison et al. 2003), where fields are searched for point sources not associated with the primary target, and subsequent spectroscopic
followup with the Keck, Palomar 200-in, Magellan, and NTT telescopes provides redshifts and AGN classifications. Preliminary results from this survey were published in [Alexander et al. (2013)], and the 30-month catalog and results will be published in Lansbury et al. (in prep).

The overall sample consists of 382 unique sources detected in the full (3 – 24 keV), soft (3 – 8 keV) or hard (8 – 24 keV) bands, of which 124 are detected in the hard band and 226 are detected in the soft band. Figure 2 shows the distribution of redshift 10 – 40 keV luminosity versus redshift for the sources in our sample. Luminosities in this plot are derived from the 8 – 24 keV count rates (if detected in that band) assuming an unabsorbed X-ray spectrum with a photon index $\Gamma = 1.8$ folded through the $\text{NuSTAR}$ response. If the source is not detected in the 8 – 24 keV band we calculate luminosities using the 3 – 24 keV or (if not detected at 3 – 24 keV) the 3 – 8 keV count rates. The median redshift for the entire $\text{NuSTAR}$ sample is $<z> = 0.76$, with a median luminosity of $<\log(L_{10-40\text{ keV}}/\text{erg s}^{-1}) >= 44.37$. For comparison we plot the distribution of AGN in the $\text{Swift}/\text{BAT}$ 70-month catalog [Baumgartner et al. (2013)]. For reference, the dashed line in Figure 2 shows the location of the knee in the luminosity function as a function of redshift from the $\text{Chandra}$-based study of [Aird et al. (2015b)], extrapolated to the 10 – 40 keV band. Together, these surveys cover a broad range of luminosity and redshift.

### 2.1. Contiguous survey fields

We have adopted uniform source detection and flux extraction methodologies across the COSMOS, ECDFS and EGS survey fields. For the ECDFS and COSMOS fields we use the source lists and supporting data products (mosaic images, exposure maps and background maps in the 3 – 24 keV, 3 – 8 keV and 8 – 24 keV energy bands) from M15 and C15, respectively. We adopt exactly the same approach for the analysis of the EGS field (Aird et al., in prep.). We summarize the analysis approach here, and refer the reader to the relevant catalog papers for details.

For source detection we convolve both the mosaic images and background maps with a 20″-radius aperture at every pixel, and determine the probability, based on Poisson statistics, that the total image counts are produced by a spurious fluctuation of the background. We generate the background maps based on the NUSKY-BGD code (see Wik et al. 2014, for details). We then identify groups of pixels in these false probability maps, using SExtractor, where the probability is less than a set threshold. Different thresholds are used in each field and in each energy band based on the expected number of spurious sources in simulations (see C15, M15 and Aird et al. in prep for specific values used for each field). We merge detections in multiple bands to produce the final catalogs, which include 61 sources (3 – 8 keV) and 32 sources (8 – 24 keV) in COSMOS, 33 sources (3 – 8 keV) and 19 sources (8 – 24 keV) in ECDFS, and 26 sources (3 – 8 keV) and 13 sources (8 – 24 keV) in EGS. The detection thresholds are chosen to ensure the catalogs are 99% reliable. Thus, we expect very few spurious sources (see M15, C15).

### 2.2. Serendipitous survey

The source-detection procedure for the serendipitous survey is the same as that outlined above, and described in detail in C15 and M15, although with a slightly different procedure for background determination. Many of the fields have bright central targets that contaminate a portion of the $\text{NuSTAR}$ field-of-view. We thus take the original images and convolve them with an annular aperture of inner radius 30″ and outer radius 90″. We rescale the counts within this annulus to a 20″ radius region based on the ratio of the effective exposures. This procedure produces maps of the local background level at every pixel based on the observed images, and will thus include any contribution from the target object. We then use these background maps, along with the mosaic images, to generate false probability maps. From here...
the source detection follows that used in the contiguous fields, using a false probability threshold of $< 10^{-6}$ across all bands. We exclude any detections within 90% of the target position, and also any areas occupied by large, foreground galaxies or known sources that are associated with the target (but are not at the aimpoint). We also exclude areas where the effective exposure is $< 20\%$ of the maximal (on-axis) exposure in a given field. Any NuSTAR fields at Galactic latitude $< 20^\circ$ are also excluded from our sample. Full details of the serendipitous survey program will be provided in Lansbury et al. (in prep), which will also indicate those serendipitous fields used in this work. In total we include 106 serendipitous sources (3 – 8 keV) and 60 (8 – 24 keV).

3. NUMBER COUNT MEASUREMENTS

To determine the number counts ($\log N$-log $S$), we adopt a Bayesian approach (see Georgakakis et al. 2008, Lehmer et al. 2012) that assigns a range of possible fluxes to a given source based on the Poisson distribution, which we then fold through the differential number counts distribution. We assume the differential number counts are described by a single power-law function:

$$\frac{dN}{dS} = K \left( \frac{S}{10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}} \right)^\beta$$

where $K$ is the normalization at $S = 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $\beta$ is the slope. Folding the Poisson likelihood for each individual source through the differential number counts given by Equation 1 accounts for the Eddington bias, allowing for the fact that a detection is more likely to be due to a positive fluctuation from a source of lower flux than vice-versa. We limit the range of possible source fluxes to a factor 3 below the nominal flux limit to prevent the probability distribution from diverging at the faintest fluxes as a result of our assumed power-law function.

We optimize the values of the parameters describing the power-law model for the differential number counts by performing an un-binned maximum likelihood fit for all sources detected in a given band (see Georgakakis et al. 2008). We also estimate differential source number counts in a number of fixed-width bins in flux using the $N_{\text{obs}}/N_{\text{mdl}}$ method of Miyaji, Hasinger & Schmidt (2001), as expanded on in Aird et al. (2010), to account for flux probability distributions. The binned estimate of the differential source number counts is then given by

$$\left[ \frac{dN}{dS} \right]_{\text{bin}} = \frac{dN}{dS} \frac{N_{\text{obs}}}{N_{\text{mdl}}}$$

where $\left[ \frac{dN}{dS} \right]_{\text{mdl}}$ corresponds to the power-law model for the differential number counts evaluated at the center of the bin. $N_{\text{mdl}}$ is the predicted number of sources in a bin (found by folding the model through the sensitivity curve) and $N_{\text{obs}}$ is the effective observed number of sources, allowing for the distribution of possible fluxes (thus a single source can make a partial contribution to multiple bins). We estimate errors based on Poisson uncertainties in $N_{\text{obs}}$ as given by Gehrels (1986).

Figure 3 (left) shows the resulting differential source number densities based on the NuSTAR samples from the four survey components combined, in the 3–8 keV band. We also compare the NuSTAR measurements to the best-fit broken power-law functions determined from Chandra surveys by Georgakakis et al. (2008) and a joint analysis of XMM-Newton and Chandra surveys by Mateos et al. (2008). We convert the Chandra (4 – 7 keV) and XMM-Newton (2 – 10 keV) number counts to match the 3–8 keV NuSTAR band assuming a $\Gamma = 1.8$ power-law X-ray spectrum. Because the bands are largely overlapping, the choice of photon spectral index does not significantly affect the results. To ease comparison between the different results we have scaled $dN/dS$ by the Euclidean slope, $S^{-2.5}$. The NuSTAR measurements constrain the slope well over the range $-14 < \log(S/\text{erg s}^{-1} \text{ cm}^{-2}) < -12.5$. The best fit values for the power law parameters in this band are: log $K = 13.84 \pm 0.04$, $\beta = -2.81 \pm 0.08$. The NuSTAR results generally agree with Chandra and XMM-Newton, although the slope of the number counts with flux is somewhat steeper. Below $S \sim 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ the NuSTAR measurements are poorly constrained, so that the location of the break in the number counts seen by Chandra and XMM-Newton cannot be independently confirmed. The difference in slope of the number counts with flux between NuSTAR and the soft X-ray telescopes is likely due the different instrument responses and the corresponding uncertainties in converting count rates to fluxes based on simple spectral models. Figure 4 (left) shows the integral compared with the extrapolated Chandra measurements.

Figure 4 (right) shows the differential source number counts in the 8 – 24 keV band, along with the best fit power law, parametrized by log $K = 14.3 \pm 0.04$, and $\beta = -2.76 \pm 0.10$. We also plot extrapolations of the Mateos et al. (2008) Chandra+ XMM-Newton counts and the Georgakakis et al. (2008) Chandra counts to the harder, largely non-overlapping 8 – 24 keV band (dotted and solid lines in Figure 3). The dotted line shows the extrapolation assuming $\Gamma = 1.8$, which is typical of unabsorbed AGNs, and systematically underpredicts the NuSTAR measurements. Using a maximum likelihood analysis, we find that a spectral photon index of $\Gamma = 1.48$ (solid line) provides the best match between the extrapolation of the Georgakakis et al. (2008) model and the NuSTAR data, indicating that a substantial population of absorbed and/or hard-spectrum sources is required to reproduce the NuSTAR measurements.

4. COMPARISON WITH THE SwIFT/BAT LOCAL AGN SAMPLE

In combination, NuSTAR and Swift/BAT sample the hard X-ray AGN population over a wide range in flux and redshift. Swift/BAT has measured the number counts at fluxes $S \lesssim 3 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ in the 15 – 55 keV band for the local ($z \lesssim 0.1$) AGN sample (Aiello et al. 2012). Although there is a gap in the flux range probed by BAT and the $S \lesssim 3 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ population probed by NuSTAR, extrapolating the BAT differential number counts to fainter fluxes indicates whether there is any evolution between the low-redshift BAT AGN population and the higher-redshift NuSTAR sources.

Figure 5 shows the NuSTAR 8 – 24 keV number counts...
Resolving the X-ray Background with *NuSTAR*

![Graphs showing differential number counts for AGN in different energy bands.](image)

**Fig. 3.** Left panel: The differential number counts for the observed 3–8 keV band. The data points (black squares) show measurements from the combined *NuSTAR* survey fields, where error bars are 1σ equivalent (i.e. 68.3% confidence level), and the black dashed line shows the best-fit power law. The solid line shows the best-fit to the number counts as measured by *Chandra* (Georgakakis et al. 2008), and the dot-dashed line shows the best fit from a combined analysis of *XMM-Newton* and *Chandra* data (Mateos et al. 2008). Right panel: The differential log N-log S in the 8–24 keV band (black squares). The solid blue line and dot-dashed lines show the *Chandra* (4–7 keV) and *XMM-Newton* measurements extrapolated to the 8–24 keV band using a photon power law index of Γ = 1.48. The blue dotted line shows the *Chandra* measurements using a steeper (Γ = 1.8) power law for the spectral extrapolation.

![Graphs showing integral number counts for AGN in different energy bands.](image)

**Fig. 4.** Integral number counts for the 3–8 keV (left) and 8–24 (right) observed bands. The grey shaded region shows the 68.3% confidence region on the integrated number counts based on the Poisson error in the number of sources weighted by the survey area as a function of flux. The blue line on the left plot shows a comparison to *Chandra* counts extrapolated from 4–7 keV.

Together with the BAT measurements from Ajello et al. (2012), which are well described by a single power-law \(dN/dS\) with slope \(\beta \approx 2.5\) (bold dashed line). We have converted the BAT 15–55 keV fluxes to the 8–24 keV band assuming a photon index of \(\Gamma = 1.7\), the value that provides the best fit to the average BAT AGN spectral model from Burlon et al. (2011). To investigate the degree to which the assumed spectral index influences the extrapolation to lower fluxes, we indicate the range (hatched region and dotted lines) if we assume \(\Gamma = 1.4\) (bottom dotted line) and \(\Gamma = 2.1\) (upper dotted line). It is clear that the extrapolation of the BAT counts to lower fluxes significantly underpredicts the *NuSTAR* measurements, even with an extremely soft spectrum inconsistent with the average measured for AGN. We thus find the *NuSTAR* measurements to be inconsistent with a simple extrapolation of the BAT sample.

**5. DISCUSSION AND CONCLUSIONS**

We have presented measurements of the number counts of AGN with *NuSTAR* in two bands, from 3–8 keV and 8–24 keV. The data span a broad range in flux,
with good constraints covering $10^{-14} \lesssim S(8 - 24\text{ keV}; \text{erg s}^{-1}\text{ cm}^{-2}) \lesssim 10^{-13}$. The $3 - 8$ keV differential source number densities are in reasonable agreement with measurements from Chandra and XMM-Newton, although the slope measured by NuSTAR is somewhat steeper. The errors on the NuSTAR data in Figure 3 do not include systematic uncertainties in the X-ray counts to flux conversion. Given this and the fact that the NuSTAR effective area curve is weighted to significantly higher ener-
gies compared to Swift/BAT. We convert the BAT 15-55 keV number counts to two
agreement with the measured NuSTAR counts. This directly confirms the existence of a population of AGN with harder spectra than those typically measured below 10 keV. The Ueda+14 model, for example, uses a spectral model with a strong Compton reflection component with a relative normalization component of $R = 1.7$. Our measurements of the rest-frame 10 - 40 keV XLF [Aird et al. (2015c)] also indicate that a significant population of AGN with hard X-ray spectra is required to reconcile our NuSTAR data with prior, lower energy XLF measurements. To what extent this results from obscur-
ation versus higher levels of reflection will be determined by spectral analysis of NuSTAR sources in the survey fields (Del Moro et al. in prep, Zappacosta et al. in prep), and from spectral modeling of high quality data from local AGN samples (Bolokovic et al. in prep).

The NuSTAR 8 - 24 keV number counts lie significantly above a simple extrapolation of the number counts at brighter fluxes, sampled by the Swift/BAT survey in the 15 - 55 keV band. The difference cannot be accounted for by uncertainties in the average spectral slope used for extrapolation (see Figure 1). The BAT data are also in tension with CXB synthesis models (see Figure 5), which are in good agreement with the NuSTAR measurements. The most natural explanation for the difference is an evolution in the hard XLF, absorption distribution, or spectral properties of AGN between the very local objects seen by BAT and the more distant ($z \sim 0.5 - 1$) NuSTAR sample that is not accounted for in the current population synthesis models.

The NuSTAR extragalactic surveys have reached depths of $S(8 - 24\text{ keV}) \approx 3 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$. Comparing to the total integrated flux of the CXB from

![Figure 5](image-url)  
Fig. 5.— The NuSTAR 8 - 24 keV number counts compared to Swift/BAT (bold dashed line). We convert the BAT 15-55 keV band to the 8 - 24 keV band using a power law with photon index $\Gamma = 1.7$ (the best-fit to the average BAT AGN spectrum in the 15 - 55 keV band). The dotted lines and hatched region show the range assuming photon index ranging from 1.4 - 2.1. The dashed line with triangles shows predictions from the CXB synthesis model of Ballantyne 2011 updated to use the Ueda 2014 luminosity function. The dashed line with circles shows predictions from the CXB model from Gilli, Comastri & Hasinger (2007).
Gilli, Comastri & Hasinger (2007), this corresponds to a resolved fraction of $35\pm5\%$ in the $8 – 24$ keV band (Figure 6). This is a significant advance compared to the 1 - 2% resolved by coded mask instruments above 10 keV (Vasudevan, Mushotzky & Gandhi 2013; Krivonos et al. 2007). This resolved fraction is in good agreement with pre-launch predictions based on CXB synthesis models (Ballantyne et al. 2011). At the current depth the NuSTAR surveys do not probe the break in the number counts distribution, expected, based on extrapolations from Chandra and XMM-Newton, to occur at $S(8 – 24$ keV)$=10^{-14}$ erg s$^{-1}$ cm$^{-2}$. Reaching these depths will be challenging, as the deep fields are currently background dominated, such that sensitivity improves only as the square root of observing time. However, additional exposure in the ECDFS is planned, along with expansion of the deep surveys to cover the CANDELS/UDS field (Grogin et al. 2011), and continuation of the serendipitous survey, which will better constrain the slope of the number counts distribution above the break and improve spectral constraints on the resolved AGN population.

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