Finding Rare AGN: XMM-Newton and Chandra Observations of SDSS Stripe 82

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ABSTRACT

We have analyzed the XMM-Newton and Chandra data overlapping ~16.5 deg² of Sloan Digital Sky Survey Stripe 82, including ~4.6 deg² of proprietary XMM-Newton data that we present here. In total, 3362 unique X-ray sources are detected at high significance. We derive the XMM-Newton number counts and compare them with our previously reported Chandra Log N-Log S relations and other X-ray surveys. The Stripe 82 X-ray source lists have been matched to multi-wavelength catalogs using a maximum likelihood estimator algorithm. We discovered the highest redshift (z = 5.86) quasar yet identified in an X-ray survey. We find 2.5 times more high luminosity (Lx > 10^{45} erg s^{-1}) AGN than the smaller area Chandra and XMM-Newton survey of COSMOS and 1.3 times as many identified by XBöötes. Comparing the high luminosity AGN we have identified with those predicted by population synthesis models, our results suggest that this AGN population is a more important component of cosmic black hole growth than previously appreciated. Approximately a third of the X-ray sources not detected in the optical are identified in the infrared, making them candidates for the elusive population of obscured high luminosity AGN in the early universe.

1 INTRODUCTION

Supermassive black holes (SMBHs) that reside in galactic centers grow by accretion in a phase where they appear as Active Galactic Nuclei (AGN). To understand AGN demography and evolution, large samples over a range of redshifts and luminosities are necessary. Extragalactic surveys provide an ideal mechanism for locating large enough samples of growing black holes to study the ensemble statistically. Large area surveys have been undertaken in the optical via, e.g., the Sloan Digital Sky Survey (SDSS, Ahn et al. 2012) and in the near-infrared (NIR) via the Wide-Field Infrared Survey Explorer (WISE Wright et al. 2010) and the UKIRT Infrared Deep Sky Survey (UKIDSS, Lawrence et al. 2007), locating over 100,000 AGN in the optical and millions of AGN candidates in the infrared.

However, optical selection is not ideal for studying high-luminosity, high-redshift AGN (quasars) that are heavily reddened or obscured. At redshifts greater than 0.5, diagnostic diagrams that use ratios of narrow emission lines to identify Type 2 (obscured) AGN (e.g., Baldwin et al. 1981, Kewley et al. 2001; Kauffmann et al. 2003) become inefficient as Hα is shifted out of the optical. Such Type 2 AGN...
can be found using alternate rest-frame optical diagnostics, using, e.g., ratios of narrow emission lines versus \( q - z \) color (TBT, Trouille et al. 2011) and versus stellar mass (MEx, Juneau et al. 2011), probing out to distances \( z < 1.4 \) and \( z < 1 \), respectively. Narrow rest-frame UV emission lines identify signatures of SMBH accretion. It is unclear whether these dividing lines can unambiguously identify signatures of SMBH accretion.

The reliability of infrared color selection varies with the depth of the data, with \textit{Spitzer} IRAC color cuts (Stern et al. 2004; Lacy et al. 2004) and \textit{WISE} color cuts (Stern et al. 2012; Assef et al. 2012) being most applicable at shallow depths. At fainter fluxes, contamination from normal galaxies can become appreciable (Cardamone et al. 2008; Donley et al. 2012; Mendez et al. 2013). The revised IRAC color selection from Donley et al. (2012) is more reliable for deeper data, yet at X-ray luminosities exceeding \( 10^{43} \text{ erg s}^{-1} \) (52% of the XMM-Newton (\textit{Chandra})-selected AGN are not recovered with this MIR identification method.

X-rays provide an alternate way to search for AGN, complementing the optical and IR identification techniques to provide a comprehensive view of black hole growth over cosmic time, because X-rays can pierce through large amounts of dust and gas. Their emission is visible out to cosmological distances as long as it is not attenuated by Compton-thick \((N_H \gtrsim 10^{24} \text{ cm}^{-2})\) obscuration. Normal star formation processes rarely exceed an X-ray luminosity above \( 10^{42} \text{ erg s}^{-1} \) (e.g., Persic et al. 2004; Brandt & Hasinger 2003), whereas AGN luminosities extend to \( \sim 10^{46} \text{ erg s}^{-1} \), making X-ray selection an efficient means for locating AGN at all redshifts. Indeed, X-ray surveys such as the \textit{Chandra} Deep Fields North (Alexander et al. 2003) and South (Giacconi et al. 2001; Xue et al. 2011), the Extended \textit{Chandra} Deep Field South (Lehmer et al. 2005; Virani et al. 2006), XMM-Newton survey of the \textit{Chandra} Deep Field South (Comastri et al. 2014; Ranalli et al. 2013), XMM-Newton and \textit{Chandra} surveys of COSMOS (Cappelluti et al. 2003; 2009; Elvis et al. 2009; Brusa et al. 2010; 2012; XBoötes; Murray et al. 2003; Kenter et al. 2005), the XMM-Newton survey of the Lockman Hole (Brüning et al. 2008), \textit{Chandra} observations of All-Wavelength Extended Groth Strip International Survey (AEGIS, Davis et al. 2007; Georgakakis et al. 2007), XDEEP2 (Goulding et al. 2012), the XMM-Newton Serendipitous Survey (Mateos et al. 2008) and the XMM-Newton campaign (Chandra, Kim et al. 2007), have identified thousands of AGN, contributing significantly to our knowledge of AGN demography and galaxy and SMBH co-evolution.

However, most of these X-ray surveys cover small (<1 deg\(^2\)) to moderate (3-5 deg\(^2\)) areas, sacrificing area for depth to uncover the faintest X-ray objects. The XMM-COSMOS (Cappelluti et al. 2003; 2008; 2009; Brusa et al. 2010), \textit{Chandra} COSMOS (Elvis et al. 2009; 2008; Civano et al. 2012), and ongoing \textit{Chandra} COSMOS Legacy Project (PI: Civano) strikes a good balance of moderate area at moderate depth to populate a large portion of the \( L_x - z \) plane. But sources that are rare, like high luminosity and/or high redshift AGN, are under-represented in these small to moderate area X-ray samples as a larger volume of the Universe must be probed to locate them.

Considerable follow-up (optical/near-infrared imaging and spectroscopy) is needed to identify X-ray sources, and multi-wavelength data are needed to classify these objects. Since spectroscopic campaigns and multi-wavelength follow-up are time intensive, the output from wide area surveys such as XBOOtes (~9 deg\(^2\); Kenter et al. 2004; Kochanek et al. 2012), ChaMP (~33 deg\(^2\); Kim et al. 2007; Trichas et al. 2012) and XMM-LSS (~11 deg\(^2\), the first part of the expanded XMM-XXL 50 deg\(^2\) survey, Pierre et al. 2004; Chiappetti et al. 2013), has taken many years to achieve. The high-redshift X-ray-selected luminosity AGN population therefore remains poorly explored, prohibiting a comprehensive view of black hole growth.

To address this gap, we have begun a wide area X-ray survey in a region that already has a rich investment in multi-wavelength data and a high level of optical spectroscopic completeness (> 400 objects deg\(^{-2}\)): the SDSS Stripe 82 region, which spans 300 deg\(^2\) along the celestial equator (-60° < R.A. < 60°, -1.25° < Dec < 1.25°). The current non-overlapping X-ray coverage in Stripe 82 from archival \textit{Chandra} and archival and proprietary XMM-Newton observations is ~16.5 deg\(^2\). The distribution of these pointings across Stripe 82 is shown in Figure 1. As we are endeavoring to increase the survey area to ~100 deg\(^2\), we dub the present survey 'Stripe 82X Pilot.' Here we follow-up on the work presented in LaMassa et al. (2013) where we focused on just the \textit{Chandra} overlap with Stripe 82, by adding in ~10.5 deg\(^2\) of XMM-Newton observations, 4.6 deg\(^2\) of which were obtained by us as part of an approved AO10 proposal (PI: Urry), with the observations performed in 'mosaic' mode. We then match both catalogs to large optical (SDSS, Ahn et al. 2012), NIR (UKIDSS and \textit{WISE}, Lawrence et al. 2007; Wright et al. 2010), ultra-violet (\textit{GALEX}, Morrissey et al. 2007) and radio datasets (FIRST, Becker et al. 1995) in this region. Observations covering Stripe 82 with \textit{Spitzer} (P.I. Richards) and analysis of Herchel observation overlapping ~55 deg\(^2\) of the region (P.I. Viero) are on-going.

In Section 2, we discuss the reduction and analysis of the archival and proprietary mosaicked XMM-Newton data in Stripe 82. We use these data to calculate areal-flux curves and in Section 3 present the Log\(N\)-Log\(S\) relations, which we compare to the \textit{Chandra} Stripe 82 number counts (LaMassa et al. 2013) and those from other X-ray surveys. We then describe in Section 4 the matching of the XMM-Newton and \textit{Chandra} X-ray source lists with multi-wavelength catalogs, producing multi-wavelength source lists. In Section 5, we describe the general characteristics of the Stripe 82X sample so far. In particular, we highlight the interesting science gaps our data are primed to fill: uncovering the population of rare high-luminosity AGN at high redshift and identifying candidates for high-luminosity obscured AGN at \( z > 1 \). We have adopted a cosmology of \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.27 \) and \( \Lambda = 0.73 \) throughout the paper.
2 XMM-NEWTON DATA REDUCTION

2.1 Archival Observations

Fifty-seven XMM-Newton EPIC non-calibration observations overlap Stripe 82. Of these, twenty-four were removed due to flaring, substantial pile-up and read-out streaks, small-window mode set-up, or extended emission spanning the majority of the detector, all of which complicate serendipitous detections of point sources in the field. We were left with 33 archival observations well suited for our analysis, listed in Table 1 and shown as red circles in Figure 1 for 3 of these we dropped the PN detector due to significant pile-up which did not affect the MOS detectors as seriously.

The raw observational data files (ODFs) were processed with XMM-Newton Standard Analysis System (SAS) version 11. SAS tasks emchain and echein are run to generate MOS1 and MOS2 event files as well as PN and PN out-of-Time (OoT) event files. OoT event results from photons detected during CCD readout, when photons are recorded at random position along the readout column in the y direction. The subsequent energy correction for these OoT events will then be incorrect. The fraction of OoT events is highest for the PN detector in full frame mode, affecting $\sim 6.3\%$ of observing time. By generating simulated OoT event files, the PN images can be statistically corrected for this effect.

Good time intervals (GTIs) were applied to the data by searching for flaring in the high energy background (10-12 keV for MOS, 12-14 keV for PN and PN OoT), removing intervals where the count rate was $\gtrsim 3\sigma$ above the average. Low energy flares were removed from this filtered event list by removing intervals where the count rate was $\gtrsim 3\sigma$ above the average in the 0.3-10 keV range. In both the high energy and low energy cleaning, GTIs were extracted from single events (i.e., PATTERN = 0).

MOS images were extracted from all valid events (PATTERN 0 to 12) whereas the PN and PN OoT images were extracted from the single and double events only (PATTERN 0 to 4). To avoid emission line features from the detector background (i.e., Al Kα at 1.48 keV), the energy range 1.45 to 1.54 keV was excluded when extracting images from both the MOS and PN detectors. The PN background also has strong emission from Cu at $\sim 7.4$ and $\sim 8.0$ keV, so the 7.2-7.6 keV and 7.8-8.2 keV ranges were also excluded when extracting images from the PN detector. The PN OoT images were scaled by 0.063 to account for the loss of observing time due to photon detection during CCD readout, and were then subtracted from the PN images. Finally, MOS and PN images were extracted in the standard 0.5-2 keV, 2-10 keV and 0.5-10 keV ranges and were added among the detectors in each energy band. 

Exposure maps were generated using the SAS task exzmap for each detector and energy range. Since vignetting, decrease in effective area with off-axis distance, increases as a function of energy, we created spectrally weighted exposure maps, i.e., the mean energy at which the maps were calculated was found assuming a spectral model where, consistent with previous XMM-Newton surveys (e.g. Cappelluti et al. 2007), $\Gamma=2.0$ in the soft band and $\Gamma=1.7$ in the hard and full bands, since the spectral slope of the soft band in AGN tends to be steeper than the hard band. The same spectral model was used to derive energy conversion factors (ECFs) to transform count rates to physical flux units, where the ECF depends on the filter for the observation and was calculated via PIMMS (see Table 2 for a summary). The exposure maps were added among the three detectors for each observation, normalized by these ECFs.

Two regions in Stripe 82 had multiple X-ray observations (ObsIDs 0050020301, 0312190401 and 0111200101, 0111200201). In order to detect sources from these overlapping observations simultaneously, the events files were mapped to a common set of WCS coordinates using SAS task attcalc to update the ‘RA NOM’ and ‘DEC NOM’ header keywords. The subsequent data products (e.g., images, exposure maps, background maps, detector masks) then share common coordinates. Before running the source detection in ‘raster’ mode (see Section 2.4), the header keywords ‘EXP JD’ and ‘INSTRUME’ for these files were updated to common values. 

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1 We note that in some observations, only one or two detectors had data. See Table 1.
2 http://heasarc.nasa.gov/Tools/w3pimms.html
3 In observations where only 2 detectors were active instead of 3, the normalization was adjusted accordingly. No normalization was necessary for observations with only 1 detector.


### Table 1. Archival XMM-Newton Observations in SDSS Stripe 82

| Obs. ID     | R.A.     | Dec    | Detectors     | Exp time (ks) |
|-------------|----------|--------|---------------|---------------|
| 0036540101  | 54.64    | 0.34   | MOS1,MOS2,PN  | 21.77         |
| 0041170101  | 45.68    | 0.11   | MOS1,MOS2,PN  | 50.04         |
| 0042341301  | 354.44   | 0.26   | MOS1,MOS2,PN  | 13.36         |
| 0056023001   | 44.16    | 0.08   | MOS1,MOS2,PN  | 23.37         |
| 0066950301   | 349.54   | 0.28   | MOS1,MOS2     | 11.45         |
| 0084230401   | 28.20    | 0.09   | PN            | 23.74         |
| 0090070201   | 10.85    | 0.84   | MOS1,MOS2,PN  | 20.53         |
| 0090090101   | 322.43   | 0.07   | MOS1,MOS2,PN  | 57.43         |
| 0101640201   | 29.94    | 0.41   | MOS1,MOS2,PN  | 10.54         |
| 0111800201   | 310.06   | -0.89  | MOS1,MOS2,PN  | 16.31         |
| 0111200101   | 40.65    | 0.00   | MOS1,MOS2,PN  | 38.39         |
| 0111200201   | 40.65    | 0.00   | MOS1,MOS2,PN  | 37.99         |
| 0116710001   | 54.20    | 0.59   | MOS1,MOS2,PN  | 7.64          |
| 0134920001   | 58.45    | -0.10  | MOS1,MOS2,PN  | 18.69         |
| 0142610001   | 46.69    | 0.00   | PN            | 65.89         |
| 0147580401   | 356.88   | 0.88   | MOS1,MOS2,PN  | 15.12         |
| 0200430101   | 55.32    | -1.32  | MOS1,MOS2,PN  | 11.46         |
| 0200480401   | 37.76    | -1.03  | MOS1,MOS2,PN  | 16.07         |
| 0203160201   | 46.22    | 0.06   | MOS1,MOS2,PN  | 15.08         |
| 0203690101   | 9.83     | 0.85   | MOS1,MOS2,PN  | 47.31         |
| 0211280001   | 355.89   | 0.34   | MOS1,MOS2,PN  | 40.68         |
| 0303110001   | 14.07    | 0.56   | MOS1,MOS2,PN  | 11.09         |
| 0303111001   | 359.55   | -0.14  | MOS1,MOS2,PN  | 9.63          |
| 0303560201   | 10.88    | 0.00   | MOS1,MOS2,PN  | 6.57          |
| 0304801201   | 323.39   | -0.84  | MOS1,MOS2,PN  | 13.27         |
| 0305750101   | 1.20     | 0.11   | MOS1,MOS2,PN  | 15.07         |
| 0307000701   | 45.20    | -1.12  | MOS1,MOS2,PN  | 15.84         |
| 0312190401   | 43.82    | -0.20  | MOS1,MOS2,PN  | 11.63         |
| 0400500301   | 19.75    | 0.65   | MOS1,MOS2,PN  | 25.94         |
| 0401180101   | 331.47   | -0.34  | MOS1,MOS2,PN  | 40.13         |
| 0402320201   | 53.64    | 0.09   | MOS1,MOS2,PN  | 10.51         |
| 0403760301   | 2.76     | 0.86   | MOS1,MOS2,PN  | 25.46         |
| 0407030101   | 5.58     | 0.26   | MOS1,MOS2,PN  | 27.15         |

1. PN detector removed from analysis due to significant pile-up.
2. Detector mask manually updated to screen out regions of pile-up and extended emission.
3. Overlapping observations that were run simultaneously through source detection software: 0056020301 and 0312190401 grouped together; 0111200101 and 0111200201 grouped together.

### Table 2. ECFs\(^1\) for Each Detector and Filter\(^2\)

| Band       | PN Thin | PN Medium | PN Thick | MOS Thin | MOS Medium | MOS Thick |
|------------|---------|-----------|----------|----------|------------|-----------|
| Soft (0.5-2 keV) | 7.45     | 7.36      | 5.91     | 2.00     | 1.87       | 1.67      |
| Hard (2-10 keV)  | 1.22     | 1.24      | 1.19     | 0.45     | 0.42       | 0.43      |
| Full (0.5-10 keV)| 3.26     | 3.25      | 2.75     | 0.97     | 0.91       | 0.85      |

1. Energy conversion factors in units of counts s\(^{-1}\)/10\(^{-11}\) erg cm\(^{-2}\) s\(^{-1}\).
2. Assuming a spectral model where \(N_H = 3 \times 10^{20}\) cm\(^{-2}\) and \(\Gamma = 2.0\) for the soft band and \(\Gamma = 1.7\) for the hard and full bands. We note that for the PN detector, ECFs were adjusted to account for masking out energy ranges corresponding to background emission lines, as described in the text. For source detection, ECFs were summed among all detectors turned on during the observation.
2.2 Proprietary Observations

We were awarded 2 XMM-Newton mosaicked pointings in AO 10 (PI: C. Megan Urry, ObsIDs: 0673000101 (‘Stripe 82 XMM field 1’), 0673002301 (‘Stripe 82 XMM field 2’)), covering ∼4.6 deg². With this observing strategy, each pointing has ∼4.56 ks of exposure time and is separated with 15′ spacing. The exposure time in the regions with greatest overlap reaches a depth of ∼12 ks. The XMM-Newton mosaic procedure enables a relatively large region to be surveyed, in this case ∼2.5 deg² per mosaic, while minimizing overhead as after the first pointing, the EPIC offset tables do not need to be calculated (PN) and uploaded (MOS). Each mosaic was made up of 22 individual, overlapping pointings, for a total observing time of 240 ks between both mosaics.

We split the events files for the mosaicked observations into individual pseudo-exposures using the SAS task emosaic_prep. Each pseudo-exposure is then reduced in the same way as the archival pointings, producing cleaned events files, spectrally weighted exposure maps and appropriately modeled background maps (see below). As with overlapping archival observations, ‘RA_NOM’, ‘DEC_NOM’, ‘EXP_ID’ and ‘INSTRUME’ were updated to common values, but ‘RA_PNT’ and ‘DEC_PNT’ also had to be set manually to reflect the center coordinates of each pointing for the point spread function (PSF) to be calculated correctly during source detection. One of the pointings from ObsID 0673002301 (pseudo-exposure field 22) was afflicted by flaring and consequently not used in the source detection. In total, approximately 4.6 deg² of Stripe 82 were covered in these observations.

2.3 Background Modeling

Following Cappelluti et al. (2007), we used the following algorithm to model the background. First we created detection masks for each detector in each energy band for each observation and then ran the SAS task eboxdetect with a low detection probability (likemin = 4) to generate a preliminary list of detected sources. The positions of these sources were then masked out when generating the background maps. Regions of significant extended emission (radius >1′), piled-up sources and read-out streaks were also masked out manually.

As noted by Cappelluti et al. (2007), the background has two components: unresolved X-ray emission which comprises the cosmic X-ray background (CXB) and local particle and detector background. The former background is subject to vignetting while the latter is not. The residual area (i.e., regions where no sources are detected) was split into two regions above the median, with low vignetting, are dominated by the CXB whereas the detector background becomes more important below the median effective exposure. We set up templates to account for these two components of the background:

\[ A M_{1,v} + B M_{1,unv} = C_1 \]  
\[ A M_{2,v} + B M_{2,unv} = C_2, \]  

where \( M_{1,v} \) and \( M_{2,v} \) are the vignetted exposure maps for the areas above and below the median effective exposure time, respectively, \( M_{1,unv} \) and \( M_{2,unv} \) are the unvignetted template exposure maps, and \( C_1 \) and \( C_2 \) are the background counts. We solve this system of linear equations for the normalizations \( A \) and \( B \). The vignetted and unvignetted exposure maps are normalized by \( A \) and \( B \) respectively and then added to obtain the background map for each detector and observation. The background maps among the multiple detectors were added, giving one background map per observation.

2.4 Source Detection

We ran the source detection algorithm using the combined images, exposure maps and background maps generated as described above. We created detector masks on the combined images using the SAS task emask. For 15 observations, we manually updated these masks to screen out regions of extended emission and piled-up sources and readout streaks, as noted in Section 2.3 (see Table 1). A preliminary list of sources was generated with the SAS task emldetect, which is a sliding box detection algorithm run in ‘map’ mode, where source counts are detected in a 5×5 pixel box with a low probability threshold (likemin = 4). The source list generated by emboxdetect is used as an input for the SAS task emldetect which performs a maximum likelihood point source detection, using a likelihood threshold \( \det_{ml} = -\ln P_{Random} \) with \( P_{Random} \) being the Poisson probability that a detection is due to random fluctuations. We ran emldetect with the option to fit extended sources, where the PSF is convolved with a β model profile. All extended sources (i.e., ext flag >0 in the emldetect outputted source list) are omitted from further analysis in this paper.

For overlapping archival observations, emboxdetect and emldetect were run in ‘raster’ mode, i.e., these tasks were run on an input list of images, exposure maps, detector masks and background maps, which were noted above were remapped to a common WCS grid. The source detection algorithm was run separately for the soft, hard and broad bands for the overlapping observations but simultaneously for the non-overlapping pointings. As an example, memory constraints precluded running emboxdetect and emldetect simultaneously for overlapping observations in multiple energy bands. The ECFs reported in Table 2 are summed among the detectors turned on for each observation and given as input in the source detection algorithm, converting count rates into physical flux units.

The 22 pointings for each mosaicked observation could not be fit simultaneously for source detection due to computational memory constraints. Instead, each group of mosaicked pointings was split into sub-groups so that source detection was run on two adjacent ‘rows’ in R.A. to accommodate overlapping pointings. Other than the pointings on the Eastern and Western edges of the mosaic, each R.A. row was included in two source detection runs to account for overlap and ensure the deepest possible exposures. Similar to the overlapping archival observations, the source detection was run separately for the soft, hard and full bands. From the source lists, we then generated a list of individual sources and searched for the inevitable duplicate identifications of the same source, since portions of every field were in more than one source detection fitting run. Similar to the algorithm used for the Serendipitous XMM-Newton Source Catalog to identify duplicates (Watson et al. 2003), if the distance
between any two sources is less than \( d_{\text{cat}} \) (where \( d_{\text{cat}} = \min(0.9 \times d_{n,1}, 0.9 \times d_{n,2}, 15', 3 \times \sqrt{\text{\text{rad}}_{\text{err}}^2 + \text{sys}_{\text{err}}^2 + \text{rad}_{\text{dec}}_{\text{err}}^2 + \text{sys}_{\text{err}}^2}) \), where \( d_{n} \) is the distance between a source and its nearest neighbor in that pointing, \( \text{rad}_{\text{dec}}_{\text{err}} \) is the positional X-ray error returned by emldetect, and \( \text{sys}_{\text{err}} \) is the systematic positional error (taken to be 1"). We then chose the source with the higher \( d_{\text{ml}} \) as the detection from which to derive the position, positional error, flux and flux error. We chose a maximum search radius of 15" based in part from the results of the simulations and matching the input simulated list to the detected source list, with this threshold maximizing identification of counterparts while minimizing spurious associations.

To merge the separate soft, hard and full band source lists into one single source list for the archival overlapping and mosaicked observations, we identified duplicate sources using the method described above. The positions among (or between, for cases where a match was found in 2 rather than 3 bands) the bands were averaged and the positional errors were added in quadrature. In our final point source list, we remove extended objects (i.e., where \( ext > 0 \) as reported by emldetect) and only include the objects where \( d_{\text{ml}} \) > 15 (5\(\sigma\) significance) in at least one of the energy bands, to reduce spurious identifications and assure our catalog contains reliable X-ray detections (see Mateos et al. 2008, Loaring et al. 2005). As summarized in Table 3 we detected 2358 X-ray sources, of which 1607 were found in archival observations and 751 were discovered in our proprietary program. Of this total number, 182 were detected only in the full band, 261 were identified solely in the soft band and 18 in just the hard band.

### Table 3. Number of Detected XMM-Newton Sources

| Band                  | Archival | Proprietary | Total |
|-----------------------|----------|-------------|-------|
| Soft (0.5-2 keV)      | 1438     | 635         | 2073  |
| Hard (2-10 keV)       | 432      | 175         | 607   |
| Full (0.5-10 keV)     | 1411     | 668         | 2079  |
| Total                 | 1607     | 751         | 2358  |

1The numbers for the individual bands refer to the sources detected at \( d_{\text{ml}} \) > 15 in that band, while the total band numbers indicate the sources detected at \( d_{\text{ml}} \) > 15 in any given band.

2.5 Monte Carlo Simulations: Source Detection Reliability & Survey Coverage

To estimate the fraction of spurious and confused sources, we compare the sources detected significantly from the simulations (\( d_{\text{ml}} \) > 15) with the input source list. We consider a detected source within 15" of an input source as a match. Any detected object lacking an input counterpart is deemed spurious. The fraction of spurious sources is 0.49%, 0.37%, and 0.20% in the soft, hard and full bands, respectively. Following the prescription of Cappelluti et al. (2007), a source is considered confused if \( S_{\text{out}}/(S_{\text{in}} + 3\sigma_{\text{out}}) > 1.5 \), where \( S_{\text{out}} \) and \( S_{\text{in}} \) are the output and input fluxes of the counterparts and \( \sigma_{\text{out}} \) is the error on the detected flux. We estimate our fraction of confused sources in the soft, hard, and full bands as 0.34%, 0.23%, and 0.34%, respectively.

From these simulations, we also accurately gauge our survey sensitivity by determining the distribution of fluxes for both input and significantly detected sources. The ratio of these distributions as a function of flux provides us with the area-flux curves shown in Figure 2, where we show the area-flux curves separately for the XMM-Newton proprietary data (\( ~\text{4.6 deg}^2 \)), proprietary and archival XMM-Newton data (\( ~\text{10.5 deg}^2 \)), XMM-Newton and Chandra coverage (\( ~\text{16.5 deg}^2 \)), and Chandra-COSMOS (\( ~\text{0.9 deg}^2 \)). For comparison; we note that the fluxes in the Chandra hard (2-7 keV) and full (0.5-7 keV) bands were converted to 2-10 keV and 0.5-10 keV ranges using the assumed spectral models of \( \Gamma = 1.7 \) for Stripe 82 and \( \Gamma = 1.4 \) for Chandra-COSMOS. We reach down to approximate flux limits (at \( ~0.1 \text{deg}^2 \) of coverage) of \( 1.4 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \), \( 1.2 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \) and \( 5.6 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \) with half-survey area at \( 4.7 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \), \( 3.1 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \) and \( 1.6 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \) in the soft, hard and full bands, respectively. From these curves, we then generate the number counts below.

3 LOGN - LOGS

We present the number density of point sources as a function of flux, i.e., the \( \text{logN} - \text{logS} \) relation. In integral form, the cumulative source distribution is represented by:

\[
N(> S) = \frac{N_s}{\Omega_i} \times \frac{1}{\Omega_i}.
\]

4 https://github.com/piero-ranalli/cdfs-sim
Finding Rare AGN: XMM-Newton and Chandra Observations of SDSS Stripe 82

Figure 2. Area-flux curves for the Stripe 82 X-ray coverage and Chandra-COSMOS [Elvis et al. 2009] for comparison in the (a) soft, (b) hard, and (c) full bands. From the XMM-Newton proprietary + archival area-flux curves, we produced the LogN-LogS relationships in Figure 3.

where \( N(S) \) is the number of sources with a flux greater than \( S \) and \( \Omega_i \) is the limiting sky coverage associated with the \( i \)th source. The associated error is the variance:

\[
\sigma^2 = \frac{1}{N_s} \sum_{i=1}^{N_s} \left( \frac{1}{\Omega_i} \right)^2.
\]  \hspace{1cm} (4)

To avoid biasing our LogN-LogS relations by the inclusion of targeted sources, we removed the closest object located within 30″ of the target R.A. and Dec, taken from RA\&OBJ and Dec\&OBJ in the FITS header. Of the 33 archival pointings, 18 had objects within 30″ of the nominal target positions. Three of these were not detected at a significant level (i.e., \( \text{det}_{\text{ml}} \geq 15 \)) in any given band and were not in our final source list. Thus, only 15 sources were excluded when generating the LogN-LogS. Of the remaining 15 archival pointings, 12 had central regions masked out due to extended emission or pile-up (presumably from the targeted source) while the other 3 had no sources detected within 30″ of the targeted position.

The number counts in the soft, hard and full bands are shown in Figure 3. We have also overplotted the upper and lower bounds of the Chandra LogN-LogS from Stripe 82 (S82 ACX) for comparison, where we have re-calculated the source fluxes and survey sensitivity from LaMassa et al. (2013) using the same spectral model applied to the XMM-Newton data. We note that 12 Chandra non-cluster pointings used for generation of the LogN-LogS presented in LaMassa et al. (2013) at least partially overlap the XMM-Newton observations, \( \sim 1.2 \) deg\(^2\). Since the hard and full bands are defined in S82 ACX up to 7 keV, the Chandra fluxes have been adjusted assuming a powerlaw model of \( \Gamma=1.7 \) to convert to the energy ranges used in our XMM-Newton analysis (i.e., the Chandra fluxes have been multiplied by factors of 1.36 and 1.2 for the hard and full bands, respectively). The XMM-Newton and S82 ACX number counts are largely consistent, with slight discrepancies apparent at moderate fluxes in the hard band (\( \sim 5 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} < S_{2-10\text{keV}} < 2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \)) and at the low XMM-Newton flux limit in the full band (\(<2 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \)). However, as noted in LaMassa et al. (2013), short exposure times in Chandra observations, which constitute the majority of Stripe 82 ACX, has an effect on the LogN-LogS normalization in the hard band, making the offset between XMM-Newton and Chandra in this energy range unsurprising.

In Figure 3 we compare the Stripe 82 ACX LogN-LogS using the spectral model from LaMassa et al. (2013) and the one used here. In LaMassa et al. (2013), we adopted a spectral model used in Chandra surveys to which we compared our results while here we used a spectral model consistent with previous XMM-Newton surveys, such as XMM-COSMOS [Cappelluti et al. 2007]. The difference in the hard band number counts is slight with this change of assumed spectral model, but shifts the normalization to lower values in the soft and especially the full band where the median offset between the 1σ error bars in the discrepant ranges is \( \sim 10\% \).

We also compare our LogN-LogS relationships with those from previous X-ray surveys, spanning from wide (2XMMi, 132 deg\(^2\); Mateos et al. 2008) to moderate (XMM-COSMOS, 2 deg\(^2\); Cappelluti et al. 2007, 2009) to
small areas (E-CDFS, 0.3 deg$^2$, XMM-CDFS, $\sim$0.25 deg$^2$; Lehmer et al. 2005; Ranalli et al. 2013). Where possible, we aim to compare our data with other XMM-Newton surveys. However, the XMM-Newton survey in the CDFS (Ranalli et al. 2013) only produced the Log$N$-Log$S$ in the hard band, so we use the Chandra E-CDFS survey (Lehmer et al. 2005) for comparison in the soft band. No previous XMM-Newton survey has produced a full band Log$N$-Log$S$, so we compare our Stripe 82 number counts with the small area Chandra-COSMOS (C-COSMOS, 0.9 deg$^2$; Elvis et al. 2009) and wide area ChaMP surveys (9.6 deg$^2$; Kim et al. 2007). As ChaMP defines the full band to be 0.5-8 keV, their fluxes were adjusted to match our 0.5-10 keV range using their adopted spectral model (i.e., multiplied by a factor of 1.18). We note that the spectral shapes over a broad band are not well constrained, making the energy conversion factors in this range approximate and comparisons with number counts using other model assumptions difficult to quantify; these comparisons are for illustrative purposes. The model predictions from Gilli et al. (2007) have also been overplotted in the soft and hard bands.

The Stripe 82 XMM-Newton number counts are consistent with previous XMM-Newton surveys in the hard band. The 2XMM Log$N$-Log$S$ from Mateos et al. (2008) is systematically higher than our data in the soft band. However, they note that their 0.5-2 keV number counts are higher than several other X-ray surveys, which attribute to the inclusion of moderately extended sources in their catalog. Similar to other surveys, we include only point sources, making this soft band discrepancy with Mateos et al. (2008) not surprising. Stripe 82 XMM-Newton is fully consistent with E-CDFS (Lehmer et al. 2005) and the model predictions from Gilli et al. (2007) in this energy range. Though the normalization for the full band Stripe 82 XMM-Newton Log$N$-Log$S$ seems low compared to ChaMP and C-COSMOS, this is likely due to differences in spectral models to convert from count rate to fluxes: ChaMP and C-COSMOS adopt a powerlaw model with $\Gamma = 1.4$ whereas we use $\Gamma = 1.7$. As shown in Figure 3(c), the difference between these two spectral models shifts the full band number counts in the right sense to account for the observed disagreement between Stripe 82 XMM-Newton and C-COSMOS and ChaMP. We also note that the ChaMP number counts seem to be somewhat higher than other Chandra surveys (LaMassa et al. 2013) while C-COSMOS shows better agreement with our calculations.

As we show below, these X-ray objects do preferentially sample the high luminosity AGN population and include candidates for interesting rare objects: reddened quasars and high luminosity AGN at high redshift. In a future paper, we will quantify the evolution of these sources by generating the quasar luminosity function, beginning with the Log$N$-Log$S$ relations presented here.

4 MULTI-WAVELENGTH SOURCE MATCHING VIA MAXIMUM LIKELIHOOD ESTIMATOR

The Stripe 82 X-ray source lists represent the XMM-Newton objects found above and the Chandra sources detected at $\geq 4.5\sigma$ level from all pointings overlapping the Stripe 82 area. In LaMassa et al. (2013), we presented only those ob-
Figure 4. Comparison of the Chandra number counts in the (a) soft, (b) hard and (c) full bands using the assumed spectral model from LaMassa et al. (2013), $\Gamma = 1.4$ in all bands (1σ confidence interval shown by red lines) and the spectral model adopted for the XMM-Newton data, $\Gamma = 1.7$ in the soft band and $\Gamma = 1.4$ in the hard and full bands (black filled circles). The spectral model assumed for this paper shifts the number counts normalization to lower values with respect to the LaMassa et al. (2013) results, with the most significant offset (i.e., where the error ranges do not overlap) in the full band, with a median discrepancy of $\sim 10\%$.

| S$_{0.5-2\text{kev}}$ (erg cm$^{-2}$ s$^{-1}$) | N(>S) deg$^{-2}$ |
|---------------------------------------------|-----------------|
| $10^{-15}$ | 1000.0 |
| $10^{-14}$ | 100.0 |
| $10^{-13}$ | 1.0 |

(a) Model used in this paper

(b) Model used in LaMassa + 2013

(c) Model used in this paper

Model used in LaMassa + 2013

*This systematic uncertainty takes into account that we used the coordinates as reported from emldetect as our attempt to use eposcorr to correct systematic astrometric offsets was unsuccessful, introducing different systematic offsets. The 1″ systematic error used here is consistent with the XMM-Newton Serendipitous Catalog procedure for estimating positional uncertainty for sources lacking independent astrometric corrections (Watson et al. 2009).*
= 7′′ (Brusa et al. 2010); the positional errors for 88% of Chandra and 99.9% of XMM-Newton sources are below the adopted search radii.

To determine the background distribution \( n(m) \), we isolate the ancillary sources within an annulus around each X-ray source, with inner and outer radii of 7′′ and 30′′ for Chandra and 10′′ and 45′′ for XMM-Newton. The inner radius is chosen to avoid the inclusion of real counterparts and the outer radius is picked to ensure a large number of sources to estimate the background while minimizing overlap with other X-ray sources. Within these annular regions, there were 53 Chandra pairs and 7 Chandra triples (~11% of the sample) and 49 XMM-Newton pairs and 3 XMM-Newton triples (~4% of the sample), i.e., only a small fraction of the background histogram has duplicate objects.

We then calculate \( q'(m) \) by first finding the magnitude distribution of ancillary objects within \( r_{\text{search}} \) of each X-ray source and dividing by the area to obtain the source density magnitude distribution. Similarly, we divide \( n(m) \) by the search area, and take the difference between the former and latter which gives us the expected source density magnitude distribution. Finally, multiplying this distribution by the search area gives us \( q'(m) \). We then normalize \( q'(m) \) to \( Q \), the ratio of the number of X-ray sources with counterparts found within \( r_{\text{search}} \) to the total number of X-ray sources, producing \( q(m) \) (see Civano et al. 2012).

From \( LR \), we then calculate a reliability value for each source:

\[
R = \frac{LR_1}{\sum_i (LR_i) + (1 - Q)}
\]

where the sum over \( LR \) is for each possible counterpart found within \( r_{\text{search}} \) around an individual X-ray source. We use \( R \) to discriminate between true counterparts and spurious associations. Since \( R \) depends on the source density and magnitude distribution of the ancillary sources, the critical \( R \) value \( (R_{\text{crit}}) \) we adopt to accept a match as ‘real’ differs among catalogs and strikes a fine balance between missing true counterparts and adding contamination from chance proximity to an unrelated source. To calibrate \( R_{\text{crit}} \), we shifted the positions of the X-ray sources by random amounts, with offsets ranging from \( \sim 21'' \) to \( \sim 35'' \), and reran the matching code. Any matches found should be due to random chance. We then plotted the distribution of reliability values for these spurious associations to estimate the contamination above \( R_{\text{crit}} \); full details regarding the estimate of false matches are given in Appendix A. We impose a lower limit on \( R_{\text{crit}} \) of 0.5, even in the cases where the reliability values for the shifted X-ray positions are consistent with zero. If there were multiple counterparts per X-ray source, or multiple X-ray sources per counterpart, the match with the highest reliability was favored.

In the on-line catalogues (available at CDS and searchable with VizieR, Ochsenbein et al. 2003), we list the X-ray sources, fluxes and matches to the ancillary multi-wavelength catalogs, including the non-aperture matched photometry. Duplicate observations of the same X-ray object between the Chandra and XMM-Newton source lists are marked in the on-line tables. Objects not included in the LogN-LogS relations, i.e., targets of observations and for Chandra objects, all sources identified in observations targeting galaxy clusters, are also noted. If the X-ray flux is not detected at a significant level in any individual band (< 4.5σ for Chandra and \( \text{det}_{\text{ml}} < 15 \) for XMM-Newton), the flux is listed as null in the on-line catalogues. A high level summary of the number of sources matched to each optical, near-infrared and ultraviolet catalog is reported in Table 4, with the magnitude/flux density distributions for these counterparts shown in Figure 4. Appendix B details the columns for the on-line versions of the catalogues.

4.1 Sloan Digital Sky Survey

Due to the high density of sources in SDSS, as well as sub-arcsecond astrometry precision, we matched the X-ray sources separately to the u, g, r, i and z bands, using single-epoch photometry from Data Release 9 (Ahn et al. 2012, DR9). A uniform 0.1′′ error was assumed for all SDSS positions (Rot & Budavári 2011). Comparing the reliability distributions for each band with the distributions for randomly shifted X-ray positions, we chose \( R_{\text{crit}} = 0.5 \) for both the Chandra and XMM-Newton source lists.

After vetting each individual band source list to include only objects exceeding \( R_{\text{crit}} \), we combined these source lists into a matched SDSS/Chandra catalog and an SDSS/XMM-Newton catalog. We visually inspected the cases where multiple SDSS objects (from separate band matchings) were paired to one X-ray source and selected the most likely counterpart by selecting the one with the greatest number of matches and/or the brightest object. We also imposed quality control cuts to assure the broad-band SEDs and derived photometric redshifts we will generate in a future paper (after careful aperture matching) are robust. We therefore require the SDSS objects to not be saturated, or blended, and to have the photometry well measured. After this vetting, every remaining SDSS match was visually inspected to remove objects contaminated by optical artifacts from e.g., diffraction spikes, or proximity to a close object that was not caught in the pipeline flagging.

We identified 748 and 1444 SDSS counterparts to Chandra and XMM-Newton sources, corresponding to 65% and 61% of the sample respectively, that exceeded \( R_{\text{crit}} \). However, 72 and 161 of these were rejected due to failing the quality control checks and visual inspection described above (marked as ‘yes’ in the ‘SDSS\_rej’ flag in the on-line catalogues, leaving 676 and 1283 reliable matches to Chandra and XMM-Newton sources, or 59% and 54% of the X-ray sources. In a follow-up paper in which we will generate the broad-band SEDs, we will use co-added data of the 50-60 epochs of Stripe 82 scans to search for counterparts for the remaining ~35% of the X-ray sources (Jiang et al. 2009, McGreer et al. 2013, for studies of \( z > 5 \) QSOs using co-added SDSS Stripe 82 data, see).

6 (NOT SATUR) OR (SATUR AND (NOT SATUR\_CENTER))
7 (NOT BLENDED) OR (NOT NODEBLEND)
8 (NOT BRIGHT) AND (NOT DEBLEND\_TOO\_MANY\_PEAKS) AND (NOT PEAKCENTER) AND (NOT NOTCHECKED) AND (NOT NOPROFILE)
4.1.1 Spectroscopy

We searched spectroscopic databases to find redshifts corresponding to our matched X-ray/SDSS catalogs, using SDSS DR9, 2SLAQ (Croom et al. 2009), WiggleZ (Drinkwater et al. 2010) and DEEP2 (Newman et al. 2012). This yielded spectroscopic redshifts for 306 Chandra sources (~27% of the sample): 286 from SDSS DR9; 10 from 2SLAQ; 3 from WiggleZ and 7 from DEEP2. For the XMM-Newton sources, 497 optical counterparts had spectroscopic redshifts (~21% of the sample): 468 from SDSS DR9, 20 from 2SLAQ, 4 from WiggleZ and 5 from DEEP2. We manually checked the spectra for the 25 SDSS sources where warning flags were set or for any object with $z > 5$: three spectra were re-fit to give more reliable redshifts, 11 were discarded due to poor spectra that could not be reliably fitted and we confirmed the redshifts for the remaining 11 objects. In Table [ref:table1] the number of reported redshifts do not include the 11 that we discarded. Twenty-eight XMM-Newton sources had spectroscopic redshifts but unreliable photometry; we retain the redshift, but not the photometric, information for these objects. In the online catalogues, we indicate the database from which the spectroscopic redshifts were found, with $z$-source of 0, 1, 2, 3 and 4 referring to SDSS, 2SLAQ, WiggleZ, DEEP2 and SDSS spectra refitted/verified by us, respectively.

4.2 WISE

For a source to be included in the WISE All Sky Source Catalog (Wright et al. 2010; Cutri et al. 2012), a SNR $> 5$ detection was required for one of the four photometric bands, W1, W2, W3 or W4, corresponding to wavelengths 3.4, 4.6, 12, and 22 $\mu$m, with resolution 6."1, 6."4, 6."5 and 12."0. The X-ray sources were matched to the W1 band since this band has the greatest number of non-null values, including both detections and upper limits. In the full Stripe 82 area, no WISE sources had null W1 detections, so we do not miss any potential WISE counterparts by matching to only the W1 band. The matching was performed on all W1 values, regardless of whether the magnitude corresponded to a detection or an upper limit (i.e., where the W1 SNR is below 2). The R.A. and Dec errors were added in quadrature to provide an estimate of the WISE astrometric error.

If any bands suffered from saturation or spurious detections associated with artifacts (i.e., diffraction spikes, persistence from a short-term latent image, scattered halo light from a nearby bright source, or optical ghost image from nearby bright source), contamination from artifacts, or moon level contamination, we consider the magnitude in that band unreliable. If every band did not pass these quality control tests, then the source is not included in our final tally since we will not use the WISE data for generating the SEDs. For extended sources (where ext_flag > 0), the magnitudes measured from the profile-fitting photometry (i.e., wnmpro, where n goes from 1-4) are unreliable. For these objects, we therefore focus on the magnitudes and quality flags associated with the elliptical apertures, wnmag, where n goes from 1-4. Again, if all bands have null elliptical magnitudes and/or non-zero quality control flags, the source is not included in our catalog. The extended sources have the WISE_ext flag set to ‘yes’ in the online catalogues.

When matching the Chandra catalog to WISE, we imposed an $R_{\text{crit}}$ of 0.75 and found 595 counterparts that passed the photometry quality control checks, or 52% of the Chandra sample. Eight of these were extended. Photometry of 30 sources was compromised, 20 of which were extended. Our $R_{\text{crit}}$ threshold for the XMM-Newton source list was 0.9, with 1324 counterparts identified with acceptable photometry (56% of the sample), of which 8 were extended. Sixty-five sources did not pass the quality control checks, of which 40 were extended. The X-ray sources with WISE counterparts removed for not passing the quality control checks are marked as ‘yes’ in the WISE_ext field in the on-line catalogues.

4.3 UKIDSS

We searched for the UKIDSS Large Area Survey (LAS) Data Release 8 [Lawrence et al. 2007; Casali et al. 2007; Hewett et al. 2008] and for NIR counterparts to the Stripe 82 X-ray sources; details regarding maintenance of the UKIDSS science archive are described by Hambly et al. (2008). We used the LAS Y J H K Source table, which contains only fields that have coverage in every filter and merges the data from multiple detections of the same object. Only primary objects were selected so that we worked with a clean input list with no duplicate NIR sources. We a priori removed objects flagged as noise, i.e., those sources with mergedClass set to zero and PNoise $\lesssim 0.05$; that is, we only retained objects that are consistent with real detections (not noise) at greater than the 2$r$ level for our candidate source list and background histograms. The UKIDSS positional uncertainties are set to NULL in the catalog; [Dye et al. 2006] quote that the internal accuracy can be ~100 mas in each coordinate and the external accuracy is ~80 mas in each coordinate. Adding the 180 mas uncertainty in quadrature for each coordinate gives a positional error of ~0."25 which we apply uniformly to all UKIDSS sources.

The X-ray source catalogs were matched separately to each UKIDSS band: $Y$ (0.97-1.07 $\mu$m), $J$ (1.17-1.33 $\mu$m), $H$ (1.49-1.78 $\mu$m) and $K$ (2.03-2.37 $\mu$m). The output matches were culled to include only sources exceeding $R_{\text{crit}}$ and these individual band lists were then combined. Based on our test of shifting the X-ray positions by random amounts, we chose the values $R_{\text{crit}} = 0.85, 0.75, 0.8$ and 0.75 for the $Y$, $J$, $H$ and $K$ bands, respectively; for the Chandra matches; we used

---

9 We consider the band to be affected by saturation if the fraction of saturated pixels exceeded 0.05, i.e., we could not rule out saturation at the 2$r$ level.

10 We consider moon$_{lev}$ to be 5 as contaminated, where moon$_{lev}$ is the number of frames affected by scattered moonlight normalized by the total number of frames in the exposure multiplied by 10, and spans from 0 $\leq$ moon$_{lev}$ $\leq$ 9.

11 The ‘priOrSec’ flag is set to zero if there are no duplicate observations of the same source or to the best ‘frameSetId’ for duplicated observations. The SQL syntax to isolate primary observations is then ‘(priOrSec = 0 OR priOrSec=frameSetId)’. 
respectively, in the XMM-Newton parts to the 1146 associated diffraction spike. We found 543 UKIDSS counterpart detections were similar, we favored the candidate with the greatest number of matches among the UKIDSS bands. We note that a handful of these multiple potential candidates were duplicate observations of a bright star or a bright star and associated diffraction spike. We found 543 UKIDSS counterparts to the 2358 Chandra sources (47%) and 1266 UKIDSS counterparts to the 2358 XMM-Newton objects (54%). None of these IR sources was affected by saturation, i.e., there were no instances where ‘MergedClass’ was set to -9 and ‘PSaturated’ (probability of saturation) was 0 for all objects.

4.4 GALEX

The GALEX catalog comprises sources detected over several surveys, including Deep, Medium and All Sky Imaging Surveys (DIS, MIS and AIS, respectively) as well as a Guest Investigator program. For a trade-off between depth and coverage, and to cleanly remove duplicate observations of the same source, we extracted objects from the MIS survey only. Since the survey has overlapping tiles (see Morrissey et al. 2005 for observation details), multiple observations of the same source can appear in the catalog. To chose the best candidate list, we queried the MIS database from Galex Release 7 for primary sources, i.e., those that are inside the pre-defined position (‘SkyGrid’) cell within the field (see Budavári et al. 2006). We further require that each primary is within 5′ of the field center. Following the prescription of Bianchi et al. (2011), we considered objects within 2.5″ as possible duplicates: if they are part of the same observation, i.e., had the same ‘photoextractid,’ they are considered unique sources but if they are from different observations, the data corresponding to the longest exposure was used. We note that in many cases, sources with the same ‘photextractid’ but different ‘objids’ (which identifies unique sources) were actually unmerged FUV and NUV detections of the same source, where one observation had either a FUV non-detection while there was a NUV detection or vice versa. However, since we matched the X-ray source lists separately to the NUV and FUV catalogs, such duplicates do not affect the results of our analysis.

The Chandra and XMM-Newton source lists were matched to this cleaned GALEX catalog using $R_{crit} = 0.5$ for each band. We used the individual source positional errors reported in the GALEX database, rather than applying a systematic positional error to all sources. Matching the NUV and FUV detections separately, rather than focusing on the GALEX sources with detections in both bands, has the advantage that we locate ultraviolet counterparts that are detected in one band and not the other. We then merged the results of the individual band matching, locating GALEX counterparts for 164 Chandra and 249 XMM-Newton objects, corresponding to 14% and 11% of each parent sample, respectively.

4.5 FIRST

Due to the low space density of both radio and X-ray sources, we matched our X-ray source lists to the FIRST (Becker et al. 1995; White et al. 1997) catalog using a simple nearest neighbor approach rather than MLE: the closest radio object within a search radius of 5″ for Chandra sources and within 7″ for XMM-Newton objects was chosen as the true counterpart. We used the FIRST catalog released in 2012, which contains all sources detected between 1993 and 2011, with a detection limit of 0.75 mJy over part of Stripe 82 (319.6° < R.A. < 49.5°, −1° < Dec < 1°), and 1 mJy detection limit for the rest of the region (Becker et al. 2012). We identified radio counterparts for 42 Chandra sources (4% of the sample) and 82 XMM-Newton objects (3% of the sample). From shifting the X-ray positions by random amounts, we expect spurious associations for 1 Chandra source within 5″ and 4 XMM-Newton objects within 7″. Two Chandra sources had 2 potential radio counterparts within r_search, but these X-ray sources were within the search radius of each other, so these duplicate potential matches are expected. Within the 7″ XMM-Newton search radius, 2 potential counterparts were found for 4 X-ray sources. In all of these cases, the nearest neighbor was also the brightest radio object.
Table 4. Number of X-ray Sources Detected in Ancillary Databases

| Catalog | Chandra | XMM-Newton | Total |
|---------|---------|------------|-------|
| X-ray   | 1146    | 2358       | 3302  |
| SDSS    | 676     | 1283       | 1959  |
| WISE    | 595     | 1324       | 1855  |
| UKIDSS  | 543     | 1266       | 1754  |
| GALEX   | 164     | 301        | 447   |
| FIRST   | 42      | 82         | 119   |
| Spec-2s | 306     | 497        | 795   |

1 Duplicate sources between the Chandra and XMM-Newton catalogs removed.

5 DISCUSSION

Here we use the results of the catalog matching to discuss general characteristics of the X-ray sources in Stripe 82, highlighting the science areas our survey is uniquely poised to investigate.

5.1 Probing the High X-ray Luminosity Regime of Black Hole Growth

We calculated full band X-ray luminosities for the sources with spectroscopic redshifts. After removing duplicate matches between the Chandra and XMM-Newton source catalogs and isolating the objects with luminosities exceeding $10^{42}$ erg s$^{-1}$, the X-ray luminosity above which there are few or no starburst-dominated X-ray sources (e.g., Persic et al. 2001; Brandt & Hasingen 2005), we confirm that 645 of the 759 Stripe 82 X-ray sources with optical spectra are AGN; the remaining sources have X-ray luminosities consistent with star-forming galaxies or low-luminosity AGN or are stars. Below, we compare the X-ray luminosity distribution with other X-ray surveys and with model predictions and comment on the interesting sources we have discovered.

5.1.1 Comparison with Other X-ray Surveys

The comparison X-ray surveys plotted in Figure 8 span from deep, small area (the GOODS and MUSYC survey of E-CDFS and CDF-S, $\sim$0.3 deg$^2$, Giavalisco et al. 2004; Treister et al. 2004; Cardamone et al. 2010), to moderate area and moderate depth (XMM and Chandra COSMOS, $\sim$2.1 deg$^2$, Cappelluti et al. 2004; Brusa et al. 2011; Civano et al. 2012), to wide area and shallow depth (XBo"otes, $\sim$9 deg$^2$, Kenter et al. 2005; Kuchanek et al. 2012). Again, we focus on only the X-ray sources with spectroscopic redshifts, with a completeness of $\sim$28%, $\sim$45% and $\sim$44% for E-CDFS + CDF-S, COSMOS and XBo"otes, respectively. For reference, the spectroscopic completeness of Stripe 82X, prior to any dedicated follow-up observations, is currently $\sim$23%, though the smaller X-ray surveys peer deeper, garnering many more faint optical counterparts where spectroscopic follow-up opportunities are limited. We report observed, full-band luminosities, which is 0.5-10 keV for the XMM-Newton surveys (obtained for XMM-COSMOS by summing the individual soft and hard band fluxes while Civano et al. 2012) provides full band fluxes for Chandra-

COSMOS objects), 0.5-7 keV for the Stripe 82 Chandra sources and XBo"otes, and 0.5-8 keV for E-CDFS + CDF-S.

As Figure 8 illustrates, survey area determines the AGN population sampled. Small area surveys (e.g., E-CDFS + CDF-S) identify faint objects but leave the high luminosity objects sparsely sampled. Moving to wider areas expands the parameter space to higher luminosities since these objects are rare and more volume must be probed in order to locate them. This becomes very apparent at $z > 2$ (Figure 8b).

Wider area surveys, such as COSMOS and XBo"otes, have higher levels of spectroscopic completeness than Stripe 82X due to dedicated multi-year spectroscopic campaigns. However, prior to any follow-up, we have identified 1.5 times more high luminosity AGN ($L_{0.5-10keV} > 3 \times 10^{44}$ erg s$^{-1}$) than XMM- and Chandra-COSMOS at all redshifts. Compared to XBo"otes, Stripe 82X pilot has $\sim$30% more $L_{0.5-10keV} > 10^{45}$ erg s$^{-1}$ AGN when considering all redshifts, and finds almost as many in the young universe. Though the current spectroscopic completeness of Stripe 82X pilot is comparatively lower, more area is covered, enabling identification of more high luminosity AGN.

However, comparing the source density of the brightest objects among these 2 wider area surveys with Stripe 82X pilot indicates that there are still more high luminosity AGN left to find. The space density of $L_{0.5-10keV} > 10^{45}$ erg s$^{-1}$ AGN found in COSMOS is 26 deg$^{-2}$ (i.e., 54 AGN in 2.1 deg$^2$) and in XBo"otes is 12 deg$^{-2}$ (104 in 9 deg$^2$), while currently Stripe 82X has a space density of 8 deg$^{-2}$ (132 AGN in 16.5 deg$^2$). We therefore anticipate that with additional spectroscopic completeness, the source density of high luminosity AGN will subsequently increase. Of the $L_{0.5-10keV} > 10^{45}$ erg s$^{-1}$ AGN already identified in Stripe 82 that have optical classifications, one is a narrow line AGN (optically classified as a ‘galaxy’) while the remaining have broad lines.

5.1.2 Comparison with Model Predictions

With the larger dataset presented here, we expand on the work of LaMassa et al. (2013) and compare the luminosity distribution of X-ray AGN we immediately identify with X-ray background population synthesis predictions of Treister et al. (2009), Gilli et al. (2007), and Ballantyne et al. (2011). We input the observed area-flux curves for Chandra and XMM-Newton into the Treister et al. (2009) simulator and convolved the predicted LogN-LogS distributions from Gilli et al. (2007) and Ballantyne et al. (2011) with our observed area-flux curves; we note that since the Gilli et al. (2007) predictions only allow the hard band flux to be defined from 2-10 keV, we corrected the output fluxes in the Chandra band to our 2-7 keV range, using our assumed spectral model where $\Gamma=1.7$. As Gilli et al. (2007) do not provide model predictions in the full band, we compare our observed full-band numbers to the models from Treister et al. (2009) and

12 Model predictions from the work of Treister et al. (2009) for a range of input values are publicly available at http://agn.astroudec.cl/jaggi/counts.html where we use their assumed spectral model of $\Gamma=1.9$ to convert the hard band luminosity bins into soft band luminosity bins required by their code.
Figures 7 and 8 are a subset of the total data from dedicated multi-year follow-up campaigns, we immediately dash, Kenter et al. 2005; Kochanek et al. 2012) have benefited Brusa et al. 2010; Civano et al. 2012) and XBo¨ otes (blue dot-and Chandra 14
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redshift and high-luminosity AGN; small area surveys (e.g., E-

surveys are necessary to sample appreciable numbers of high-

redshift and high-luminosity AGN; small area surveys (e.g., E-

CDFS + CDF-S, black, Giavalisco et al. 2004; Treister et al.

CDFS + CDF-S, black, Giavalisco et al. 2004; Treister et al.

Figure 6. X-ray luminosity distribution for Stripe 82X sources
(red filled) compared to other X-ray selected samples for
(a) all sources with spectroscopic redshifts and (b) objects
with spectroscopic redshifts greater than 2. Wider area sur-
veys are necessary to sample appreciable numbers of high-

redshift and high-luminosity AGN; small area surveys (e.g., E-

CDFS + CDF-S, black, Giavalisco et al. 2004; Treister et al.

Ballantyne et al. (2011). The predicted luminosity bins repre-
sent intrinsic, rest-frame luminosities, while the Stripe 82X
data are observed luminosities. We removed any Chandra
points that overlapped XMM-Newton pointings since the
latter has more effective area. Since we did detect a handful
of Chandra sources in these removed pointings that were
not identified by XMM-Newton, the histograms presented in
Figures 7 and 8 are a subset of the total data.

The models from Gilli et al. (2007) predict more AGN
at all redshifts and more high luminosity (> 10^{45} \text{ erg} \ s^{-1}) AGN at \( z > 2 \) than the Treister et al. (2009)
models while the Ballantyne et al. (2011) model predicts more
\( L > 10^{44} \text{ erg} \ s^{-1} \) AGN than the Treister et al. (2009)
model. As Ballantyne et al. (2011) produces predictions based on
three different input luminosity functions (Ueda et al. 2003;
La Franca et al. 2003; Aird et al. 2010), which show a sig-
nificant range in expected AGN numbers within most luminos-
ity bins, discrepancies among models can be attributed
to differences in luminosity functions. Gilli et al. (2007) uses
the XLF from Hasinger et al. (2003) in the 0.5-2 keV band,
estimating the contribution of moderately obscured AGN
\((10^{21} \text{ cm}^{-2} < N_H < 10^{24} \text{ cm}^{-2})\) in the hard band by cal-
dulating the difference between the Ueda et al. (2003) and
La Franca et al. (2003) XLFs and the Hasinger et al. (2003)
XLF (after converting the latter to the hard band). The
predictions from Treister et al. (2009) are calibrated on the
hard band XLF from Ueda et al. (2003).

Due to our limited spectroscopic completeness (see Sec-
tion 4.1.1), we have identified fewer AGN than predicted
given the constraints from our data. However, these ‘miss-
ing’ objects are predominantly at low to moderate lumi-
nosities (< 10^{45} \text{ erg} \ s^{-1}). When considering objects at all
spectroscopic redshifts, we found more high luminosity AGN
than predicted by the Treister et al. (2009) model, most of
those predicted by the Gilli et al. (2007) model and a signif-
cant fraction to most, depending on the luminosity function,
of those predicted by the Ballantyne et al. (2011) model.
The same result applies to objects at \( z > 2 \) in the hard
and full bands (though we do find more high luminosity ob-
jects than the Ballantyne et al. (2011) predictions based on
the Aird et al. (2010) models in these bands), while in the
soft band, the Treister et al. (2009) and Ballantyne et al.
(2011) models predict slightly more high luminosity objects
than we have yet discovered. Currently, the discrepancies be-
tween our observations and the Treister et al. (2009) model
are within ~2σ assuming Poisson uncertainties. Given the
lower space density of these objects compared to surveys
with higher spectroscopic completeness (i.e., Section 5.1.1),
seems clear that more high luminosity AGN will be con-
firmed. Even a small increase in the high luminosity popu-
lation would surpass the predictions of Gilli et al. (2007) and
the more conservative numbers of Ballantyne et al. (2011).
We also expect that our luminosity distribution is systemat-
ically lower than the predictions as the latter use instrinsic,
rather than observed, luminosities as input. The systematic
effect would shift the Stripe 82X sources into higher luminos-
ity bins if corrected for absorption, making our comparison
at high luminosities conservative.

Finding a greater number of high X-ray luminosity
AGN relative to the model predictions is consistent with
what was reported earlier by LaMassa et al. (2013), namely,
that population synthesis models need to be refined to prop-
erly account for the high luminosity AGN regime. As this
unexplored population is more numerous than predicted,
quantifying its impact on AGN demography and evolution is
critical for fully understanding black hole growth. Increased
spectroscopic completeness will inform us as to the signifi-
cance of the offset.
Figure 7. Luminosity distribution for Stripe 82X sources (red filled) for all sources with spectroscopic redshift compared to population synthesis models from Treister et al. (2009, dash-dotted black line), Gilli et al. (2007, dashed blue line) and Ballantyne et al. (2011, assuming different luminosity functions noted in the caption) in the (top) soft, (middle) hard and (bottom) full energy bands; models from Gilli et al. (2007) over the full X-ray band are not available. At high luminosities, we have already identified more AGN than predicted by the Treister et al. (2009) model and almost as many as predicted by the Gilli et al. (2007) model and Ballantyne et al. (2011) model, depending on the assumed luminosity function.

Figure 8. Same as Figure 7 but for spectroscopic redshifts greater than 2. We identified more high luminosity AGN than predicted by Treister et al. (2009) and Ballantyne et al. (2011) with the Aird et al. (2010) luminosity function as input in the hard and full bands, suggesting the Stripe 82X large area survey will provide important constraints to black hole growth in the high-luminosity, high-redshift regime.
In Figure 10, we plot the WISE $W_1 - W_2$ color as a function of $W_1$ for the 1713 Stripe 82 X-ray sources with significant detections (SNR $\geq 2$) in both bands on top of the contours indicating the density $(10^5, 10^4, 10^3, 10^2$ objects per contour) of all WISE objects in 300 deg$^2$ if Stripe 82, with our X-ray objects overplotted as red stars and the $W_1 - W_2 \geq 0.8$ AGN candidate color cut (e.g., Stern et al. 2012; Assef et al. 2012) marked by the dashed line. About half of our X-ray objects have redder colors, while 2/3 of the objects with spectra that are X-ray identified as AGN also exceed this boundary. The 166 spectroscopically identified X-ray AGN ($L_x > 10^{42}$ erg s$^{-1}$) with bluer colors are shown by the green circles.

\section{5.2 SMBH Growth at High Redshift}

Though $z > 5$ quasars identified by SDSS have been followed up with dedicated Chandra observations (e.g., Brandt et al. 2002; Shemmer et al. 2006; Vignali et al. 2009), not many have been found in X-ray surveys. Thus far, only 6 have been confirmed spectroscopically: $z = 5.19$ in CDF-N (Barger et al. 2003), $z = 5.4$ from the Chandra Large Area Synoptic X-ray Survey (Steffen et al. 2004), $z = 5.3$ and $z = 5.07$ from Chandra-COSMOS (Civano et al. 2011), and 2 from ChAMP, with the most distant object having a redshift of 5.41 (Trichas et al. 2012). None have been located in the 4 Ms of CDF-S, demonstrating that area trumps depth for locating these very high redshift sources. In this pilot survey of Stripe 82X, we have discovered only one object beyond a redshift of 5, but it is the most distant X-ray selected quasar from an X-ray survey to date, at $z = 5.86$ with $L_{0.5-10keV} = 4.4 \times 10^{45}$ erg s$^{-1}$ (Chandra source, MSID = 165442). The SDSS spectrum of this source is shown in Figure 9 revealing broad Lyα (i.e., this source is classified as a broad line AGN).

Such objects are expected to be quite rare. For instance, model predictions from Freister et al. (2009) estimate that only 3 AGN at $z > 5$ with $L_{0.5-10keV} > 10^{45}$ erg s$^{-1}$ exist in this survey area, given the observed full band area-flux curves. Similarly, using the soft band area-flux curves, the models from Gilli et al. (2007) predict 5 AGN at $z > 5$ with $L_{0.5-2keV} > 10^{45}$ erg s$^{-1}$, but less than one when applying an exponential decline to the high-$z$ luminosity function. These types of objects will be below the flux limit of eRosita (Merloni et al. 2012; Kolodzig et al. 2012), making the Stripe 82X survey important for constraining black hole formation models.

\section{5.3 Obscured AGN Beyond the Local Universe}

\subsection{5.3.1 WISE AGN Candidates}

In Figure 10 we plot the WISE $W_1 - W_2$ color as a function of $W_1$ for the 1713 Stripe 82 X-ray sources with significant detections (SNR $\geq 2$) in both bands on top of the contours indicating the density $(10^5, 10^4, 10^3, 10^2$ objects per contour) of all WISE objects in 300 deg$^2$ if Stripe 82, with our X-ray objects overplotted as red stars and the $W_1 - W_2 \geq 0.8$ AGN candidate color cut (e.g., Stern et al. 2012; Assef et al. 2012) marked by the dashed line. About half of our X-ray objects have redder colors, while 2/3 of the objects with spectra that are X-ray identified as AGN also exceed this boundary. The 166 spectroscopically identified X-ray AGN ($L_x > 10^{42}$ erg s$^{-1}$) with bluer colors are shown by the green circles.

\subsection{5.3.2 Optically Normal Galaxies}

At $z > 0.5$, diagnostic line ratio diagrams used to discriminate between Type 2 AGN and star-forming galaxies (e.g., Baldwin et al. 1981; Kewley et al. 2001; Kauffmann et al. 2003) become challenging in optical surveys as Hα is shifted...
out of the rest-frame bandpass. Candidates for obscured AGN would then have to be identified via alternative optical diagnostics, such as ratios of narrow emission lines versus stellar mass (MEX, Juneau et al. 2011) or vs. rest frame g − z color (TBT, Trouille et al. 2011). Follow-up of type 2 AGN candidates with ground-based NIR spectroscopy to observe the traditional BPT line diagnostics is also possible, but as the metallicity of host galaxies evolves with redshift, the applicability of line ratios calibrated for galaxies at z < 0.5 to higher redshift systems may not cleanly separate star-forming from active galaxies. Conversely, calculating an object’s X-ray luminosity provides a more efficient identification mechanism. In our survey, we have identified 22 X-ray AGN at z > 0.5 with luminosities exceeding 10^{43} erg s^{-1} that were classified as galaxies in SDSS, 2SLAQ or DEEP2 based on their optical spectra. One of these objects is extremely bright as noted above, L_\text{IR} = 10^{45} \text{erg s}^{-1}, and is an example of the kind of highly luminous obscured AGN our survey is designed to uncover. Currently these sources only represent 3% of our AGN sample, but we expect that more of these objects will be discovered during our spectroscopic follow-up campaign.

5.3.3 Optical Dropouts

We identified 748 and 1444 optical counterparts to the Chandra and XMM-Newton sources, respectively, though 72 and 161 are discarded due to poor photometry. How many of the ∼400 Chandra and ∼900 XMM-Newton X-ray objects lacking SDSS counterparts (r > 23) do we find in the infrared? Most of these optical dropouts are either reddened by large amounts of dust or live at high redshift, so that the rest-frame optical light is shifted to redder wavelengths.

To answer this question, we look at two classes of optical dropouts: the X-ray sources with optical counterparts below R_{\text{crit}}, including objects where no SDSS counterparts are found within the search radius, and the subset of X-ray sources without any optical counterpart within r_{\text{search}}. In the former case, a true counterpart can be misclassified as a random association, especially if it is faint. The latter number then gives us a lower limit on the number of infrared bright optical dropout X-ray sources. Comparison of the flux limits for SDSS, WISE and UKIDSS to the type 1 quasar SED (i.e., broad line AGN) from Elvis et al. (1994) demonstrate that SDSS is deeper than the WISE or UKIDSS observations, making the detection of IR sources that are SDSS drop-outs a significant finding. We summarize these results in Table 5 detailing the number of optical dropouts found in the IR generally and the numbers identified in the WISE and UKIDSS catalogs specifically. We note that the greater percentage of optical dropouts that have no counterpart within the search radius for the Chandra catalog compared to XMM-Newton can be understood by the larger search radius used for the latter catalog.

Over 30% of the optical dropouts are detected in the infrared, making them candidates for the elusive population of obscured high luminosity AGN at high redshift. We plot the WISE colors of the 151 dropouts (∼12% of optical dropouts) that have significant W1, W2 and W3 detections (i.e., SNR > 2 in each band) in Figure 11 for the optical dropout X-ray sources. The WISE colors are overlaid on the diagram from Wright et al. (2010), where the colored loci represent different classes of astronomical objects. A majority of the optical dropouts detected in X-rays have WISE colors consistent with active galaxies, with nearly half having infrared colors akin to quasars. These are prime candidates for high-luminosity Type 2 AGN or highly reddened quasars and will be followed up by us with NIRSPEC on Keck and ISAAC on ESO’s VLT. For the remaining 840 optical dropouts without infrared associations (25% of the X-ray sample), deeper optical and infrared imaging is necessary to identify the multi-wavelength counterparts to the X-ray sources.

| Catalog | Chandra | XMM-Newton | Total1 |
|---------|---------|------------|--------|
| No SDSS counterpart within r_{\text{search}} or above R_{\text{crit}} | | | |
| X-ray | 398 | 914 | 1312 |
| IR2 | 112 | 371 | 472 |
| WISE | 95 | 313 | 401 |
| UKIDSS | 43 | 149 | 189 |
| No SDSS counterpart within r_{\text{search}} | | | |
| X-ray | 317 | 486 | 781 |
| IR2 | 88 | 161 | 240 |
| WISE | 73 | 124 | 192 |
| UKIDSS | 37 | 82 | 116 |

1. After removing duplicate sources between the Chandra and XMM-Newton catalogs.
2. Detected in WISE or UKIDSS.
CONCLUSIONS

We have reduced and analyzed the $\sim 10.5 \text{ deg}^2$ of XMM-Newton data overlapping SDSS Stripe 82, including $\sim 4.6 \text{ deg}^2$ of proprietary data awarded to us in AO 10. From these observations, we detected 2358 unique X-ray sources at high significance, with 2073, 607 and 2079 in the soft (0.5-2 keV), hard (2-10 keV), and full (0.5-10 keV) bands, respectively. The LogN-LogS relations show general agreement with previous surveys in these bands, given the effect that choice of spectral model affects the normalization in the full band. Using a maximum likelihood estimator algorithm (Sutherland & Saunders 1992; Brusa et al. 2007, 2009; Cardamone et al. 2008; Luo et al. 2010; Brusa et al. 2011; Civano et al. 2012), we identified multi-wavelength counterparts to Stripe 82 X-ray sources, finding:

- 1892 optical matches from SDSS, of which 759 have spectroscopic redshifts; 1855 WISE counterparts; 1754 UKIDSS matches; 447 ultraviolet counterparts from GALEX; and 119 radio sources from FIRST (using nearest neighbor matching rather than MLE due to low source densities).

- Focusing on the subset of sources with spectroscopic redshifts, Stripe 82X harbors more high luminosity ($L_x \geq 10^{45} \text{ erg s}^{-1}$) AGN than E-CDFS and CDFS ($\sim 0.3 \text{ deg}^2$, Cardamone et al. 2010), XMM- and Chandra-COSMOS ($\sim 2.1 \text{ deg}^2$, Cappelluti et al. 2003; Brusa et al. 2014; Civano et al. 2012) and even the larger XBoötes survey ($\sim 9 \text{ deg}^2$, Kenter et al. 2003; Kochanek et al. 2012). Though these other surveys benefited from years of spectroscopic follow-up, Stripe 82X covers a wider area and thereby already uncovers more rare objects (high luminosity AGN at all redshifts and in the early universe, at $z > 2$). These numbers will increase with the spectroscopic follow-up we are currently undertaking.

- We have compared the luminosity distribution of X-ray sources with spectroscopic redshifts with the population synthesis model predictions from Treister et al. (2009), Gilli et al. (2007) and Ballantyne et al. (2011) taking into account the observational constraints of our observed area-flux curves in the soft, hard and full X-ray bands. As we showed in LaMassa et al. (2013) using a subset of these data and the full-band (Treister et al. 2009) model predictions given our area-flux curves, we discovered more high luminosity ($> 10^{45} \text{ erg s}^{-1}$) AGN than predicted by Treister et al. (2009). Though the Gilli et al. (2007) and Ballantyne et al. (2011) models predict more AGN, we have found most of those predicted at high luminosity (depending on the luminosity function for the Ballantyne et al. (2011) model), and this number will continue to increase with our spectroscopic follow-up. Refinement to models is clearly indicated to better account for this important regime of black hole growth. As these redshift, high luminosity AGN are more numerous than previously predicted, understanding their census, evolution and connection to the host galaxy becomes an important piece in completing the puzzle of cosmic black hole growth.

- We have found the most distant, spectroscopically confirmed X-ray selected quasar in an X-ray survey to date, at $z = 5.86$.

- About a third of the X-ray sources that are optical dropouts are identified in the infrared, making them candidates for reddened quasars and/or high luminosity Type 2 AGN at high redshift. Most of those with significant detections in the W1, W2 and W3 WISE bands have colors consistent with active galaxies, with more than half of them having quasar colors. We have a Keck-NIRSPEC campaign and were awarded ESO VLT ISAAC DDT time to follow-up these objects.

The Stripe 82X survey provides an important pathfinder mission to eRosita, scheduled to be launched in 2014, which will survey the entire sky in 0.5-10 keV X-rays, though with a poorer resolution than Chandra and XMM-Newton ($\sim 25\arcsec$) and with an 0.5-2 keV flux limit that is 5 times higher than our proprietary XMM-Newton mosaiced observations (Merloni et al. 2012). eRosita expects to uncover millions of AGN, of which a few tens will be $z > 6$ QSOs. An efficient method will then need to be devised to isolate the very high redshift population: results of Stripe 82X, with the wealth of multi-wavelength data, will help to inform robust identification techniques applicable to eRosita.

In other luminosity ranges, X-ray selection has uncovered a different, if overlapping, population of AGN compared to optical selection. While the jury is still out on how this impacts black hole growth at high luminosity, it is clear that the answer requires large samples selected at X-ray energies, so that the optical- and X-ray samples can be compared.

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APPENDIX A: RELIABILITY THRESHOLDS FOR COUNTERPART SELECTION

As mentioned in the main text, our goal is to optimize selection of multi-wavelength counterparts to the Stripe 82 X-ray sources by maximizing the number of true associations while minimizing contamination from chance coincidences. We inspected the distribution of source ‘reliabilities’ calculated via MLE and picked a critical threshold ($R_{\text{crit}}$) above which we expect a vast majority of the ancillary objects to represent true counterparts. By shifting the X-ray positions by random amounts and running the MLE code, the distribution of resulting reliabilities provides an empirical estimate of the contamination in our matched catalogs.

In Figures A1 - A7, we compare the reliability distribution of each wavelength band to which we matched (solid black histogram) with the reliability distribution after shifting the X-ray positions (by $\sim$21$''$ to $\sim$35$''$) overplotted (blue histogram). The dotted line indicates the specific $R_{\text{crit}}$ value we used for that band. In the captions, we note the number of spurious associations expected, i.e., ancillary counterparts matched to random positions on the sky, above $R_{\text{crit}}$.

We stress that contamination percentages that can be calculated from this test are not exact, but are instead meant to provide an empirical method for calibrating the reliabilities on a band-by-band basis. As in all multi-wavelength surveys, a handful of true counterparts may be missed, falling below $R_{\text{crit}}$, while several random coincident matches may be promoted as real matches. However, our empirical tests indicate that this effect is at the few percent level at most.
Figure A2. Reliability distributions for each SDSS band matched to XMM-Newton sources. The number of spurious associations above $R_{\text{crit}}$ is predicted to be 12, 22, 28, 28 and 34 in the $u$, $g$, $r$, $i$ and $z$ bands, respectively. The dot-dash line indicates the adopted reliability threshold for claiming a counterpart.

Figure A3. Reliability distributions for WISE band W1 matched to (left) Chandra sources and to (right) XMM-Newton objects. The number of spurious associations above $R_{\text{crit}}$ is predicted to be 6 for the Chandra source list and 7 for the XMM-Newton catalog. The dot-dash line indicates the adopted reliability threshold for claiming a counterpart.

Figure A4. Reliability distributions for each UKIDSS band matched to Chandra sources. The number of spurious associations above $R_{\text{crit}}$ is predicted at 8, 8, 5 and 5 in the $Y$, $J$, $H$ and $K$ bands, respectively. The dot-dash line indicates the adopted reliability threshold for claiming a counterpart.

Figure A5. Reliability distributions for each UKIDSS band matched to XMM-Newton sources. The number of spurious associations above $R_{\text{crit}}$ is predicted to be 21, 30, 21 and 27 in the $Y$, $J$, $H$ and $K$ bands, respectively. The dot-dash line indicates the adopted reliability threshold for claiming a counterpart.
Figure A6. Reliability distributions for each GALEX band matched to Chandra sources. When shifting the X-ray positions by random amounts and re-running the MLE code, we find no spurious associations above $R_{crit}$ in either band. The dot-dash line indicates the adopted reliability threshold for claiming a counterpart.

Figure A7. Reliability distributions for each GALEX band matched to XMM-Newton sources. We find two spurious counterparts above $R_{crit}$ in the NUV band and one in the FUV band. The dot-dash line indicates the adopted reliability threshold for claiming a counterpart.
### APPENDIX B: COLUMN DESCRIPTIONS FOR ON-LINE VERSIONS OF THE CATALOGS

Non-significant X-ray fluxes have zero values in the online catalogs. When reporting the ancillary multi-wavelength data, numeric values of -999 and null strings indicate that a reliable counterpart was not identified for that X-ray source.

#### B1 Chandra

1. **MSID**: Chandra Source Catalog identification number ([Evans et al.])(Evans et al. [2010])
2. **ObsID**: Chandra observation identification number
3. **RA**: Chandra RA (J2000)
4. **Dec**: Chandra Dec (J2000)
5. **RADecErr**: Chandra positional error (arcsec)
6. **Dist**: Distance to nearest Chandra source (arcsec)
7. **Soft Flux**: 0.5-2 keV flux (10^{-14} erg cm^{-2} s^{-1}). Set to 0 if flux is not significant at >4.5σ level.
8. **Soft Flux Error High**: higher bound on 0.5-2 keV flux (10^{-14} erg cm^{-2} s^{-1}). If flux is 0, this is the flux upper limit.
9. **Soft Flux Error Low**: lower bound on 0.5-2 keV flux (10^{-14} erg cm^{-2} s^{-1}).
10. **Hard Flux**: 2-7 keV flux (10^{-14} erg cm^{-2} s^{-1}). Set to 0 if flux is not significant at >4.5σ level.
11. **Hard Flux Error High**: higher bound on 2-7 keV flux (10^{-14} erg cm^{-2} s^{-1}). If flux is 0, this is the flux upper limit.
12. **Hard Flux Error Low**: lower bound on 2-7 keV flux (10^{-14} erg cm^{-2} s^{-1}).
13. **Full Flux**: 0.5-7 keV flux (10^{-14} erg cm^{-2} s^{-1}). Set to 0 if flux is not significant at >4.5σ level.
14. **Full Flux Error High**: higher bound on 0.5-7 keV flux (10^{-14} erg cm^{-2} s^{-1}). If flux is 0, this is the flux upper limit.
15. **Full Flux Error Low**: lower bound on 0.5-7 keV flux (10^{-14} erg cm^{-2} s^{-1}).
16. **Lum Soft**: log 0.5-2 keV luminosity (erg s^{-1})
17. **Lum Hard**: log 2-7 keV luminosity (erg s^{-1})
18. **Lum Full**: log 0.5-7 keV luminosity (erg s^{-1})
19. **In XMM**: Set to ‘yes’ if X-ray source is in the XMM-Newton Stripe 82 catalog
20. **Removed Log N Log S**: Set to ‘yes’ if X-ray source was not part of the Log N - Log S relation published in ([LaMassa et al.])(LaMassa et al. [2013])
21. **SDSS Rej**: Set to ‘yes’ if SDSS counterpart is found but rejected due to poor photometry.
22. **SDSS Objid**: SDSS object identification number
23. **SDSS RA**: SDSS RA (J2000)
24. **SDSS Dec**: SDSS Dec (J2000)
25. **SDSS Rel**: MLE reliability of SDSS match to X-ray source
26. **SDSS Dist**: Distance between X-ray and SDSS source (arcsec)
27. **u Mag**: SDSS u mag
28. **u Err**: SDSS u mag error
29. **g Mag**: SDSS g mag
30. **g Err**: SDSS g mag error
31. **r Mag**: SDSS r mag
32. **r Err**: SDSS r mag error
33. **i Mag**: SDSS i mag
34. **z Err**: SDSS i mag error
35. **u Mag**: SDSS u mag
36. **z Err**: SDSS z mag error
37. **Specobjid**: SDSS spectroscopic object identification number
38. **Class**: optical spectroscopic class (if available)
39. **Redshift**: spectroscopic redshift
40. **z Src**: source of spectroscopic redshift; 0 - SDSS, 1 - 2SLAQ, 2 - WiggleZ, 3 - DEEP2, 4 - SDSS spectra refit/verified by us
41. **WISE Name**: WISE name
42. **WISE RA**: WISE RA (J2000)
43. **WISE Dec**: WISE Dec (J2000)
44. **WISE sigra**: WISE RA error (arcsec)
45. **WISE sigdec**: WISE Dec error (arcsec)
46. **WISE Rel**: MLE reliability of WISE match to X-ray source
47. **WISE Dist**: Distance between X-ray and WISE source (arcsec)
48. **W1**: WISE W1 mag. All WISE magnitudes are from profile-fitting photometry, unless the WISE_ext flag is set to ‘yes,’ in which case the magnitudes are associated with elliptical apertures.
49. **W1sig**: WISE W1 error
50. **W1 SNR**: WISE W1 SNR. Any WISE magnitudes with SNR <2 are upper limits.
51. **W2**: WISE W2 mag
52. **W2sig**: WISE W2 error
53. **W2 SNR**: WISE W2 SNR
54. **W3**: WISE W3 mag
55. **W3sig**: WISE W3 error
56. **W3 SNR**: WISE W3 SNR
57. **W4**: WISE W4 mag
58. **W4sig**: WISE W4 error
59. **W4 SNR**: WISE W4 SNR
60. **WISE ext**: Set to ‘yes’ if WISE source is extended
61. **WISE rej**: Set to ‘yes’ if WISE counterpart is found but rejected for poor photometry
62. **UKIDSS ID**: UKIDSS ID
63. **UKIDSS RA**: UKIDSS RA (J2000)
64. **UKIDSS Dec**: UKIDSS Dec (J2000)
65. **UKIDSS Rel**: MLE reliability of UKIDSS match to X-ray source
66. **UKIDSS Dist**: Distance between X-ray and UKIDSS source (arcsec)
67. **Y Mag**: UKIDSS Y mag
68. **Y sig**: UKIDSS Y error
69. **H Mag**: UKIDSS H mag
70. **H sig**: UKIDSS H error
71. **J Mag**: UKIDSS J mag
72. **J sig**: UKIDSS J error
73. **K Mag**: UKIDSS K mag
74. **K sig**: UKIDSS K error
75. **UKIDSS rej**: UKIDSS counterpart found but rejected for poor photometry
76. **GALEX Objid**: GALEX object identification number
77. **GALEX RA**: GALEX RA (J2000)
78. **GALEX Dec**: GALEX Dec (J2000)
79. **NUV_poserr**: GALEX NUV positional error (arcsec)
80. **FUV_poserr**: GALEX FUV positional error (arcsec)
81. **GALEX Rel**: MLE reliability of GALEX match to X-ray source
82. **GALEX Dist**: Distance between X-ray and GALEX source (arcsec)
| Column Name          | Description                                                                 |
|---------------------|-----------------------------------------------------------------------------|
| NUV\_mag            | GALEX NUV mag                                                               |
| NUV\_magerr         | GALEX NUV error                                                            |
| FUV\_mag            | GALEX FUV mag                                                               |
| FUV\_magerr         | GALEX FUV error                                                            |
| FIRST\_Name         | IAU Name of FIRST counterpart                                             |
| FIRST\_RA           | FIRST RA (J2000)                                                           |
| FIRST\_Dec          | FIRST Dec (J2000)                                                          |
| FIRST\_Dist         | Distance between X-ray and FIRST source (arcsec)                           |
| FIRST\_Flux         | FIRST 5 GHz Flux Density (Jy)                                              |
| FIRST\_err          | FIRST 5 GHz Flux Density error (Jy)                                        |

### XMM-Newton

1. **Rec\_no**: Unique record number assigned to each XMM-Newton source
2. **ObsID**: XMM-Newton observation identification number
3. **RA**: XMM-Newton RA (J2000)
4. **Dec**: XMM-Newton Dec (J2000)
5. **RA\_Dec\_Err**: XMM-Newton positional error (arcsec)
6. **Dist\_nn**: Distance to nearest XMM-Newton source (arcsec)
7. **Soft\_flux**: 0.5-2 keV flux \(10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\). Flux is 0 if \(\text{det}\_\text{err} < 15\) in the soft band.
8. **Soft\_flux\_err**: error in 0.5-2 keV flux \(10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\).
9. **Hard\_flux**: 2-10 keV flux \(10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\). Flux is 0 if \(\text{det}\_\text{err} < 15\) in the hard band.
10. **Hard\_flux\_err**: error in 2-10 keV flux \(10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\).
11. **Full\_flux**: 0.5-10 keV flux \(10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\). Flux is 0 if \(\text{det}\_\text{err} < 15\) in the full band.
12. **Full\_flux\_err**: error in 0.5-10 keV flux \(10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\).
13. **Lum\_soft**: log 0.5-2k keV luminosity \(\text{erg} s^{-1}\)
14. **Lum\_hard**: log 2-10 keV luminosity \(\text{erg} s^{-1}\)
15. **Lum\_full**: log 0.5-10 keV luminosity \(\text{erg} s^{-1}\)
16. **In\_Chandra**: Set to ‘yes’ if source is found in the Chandra catalog.

### Removed Log N Log S

- Set to ‘yes’ if source is removed from Log N-Log S calculation presented in the main text.

### SDSS

- **SDSS\_Rej**: Set to ‘yes’ if SDSS counterpart is found but rejected due to poor photometry.
- **SDSS\_Objid**: SDSS object identification number
- **SDSS\_RA**: SDSS RA (J2000)
- **SDSS\_Dec**: SDSS Dec (J2000)
- **SDSS\_Rel**: MLE reliability of SDSS match to X-ray source
- **SDSS\_Dist**: Distance between X-ray and SDSS source (arcsec)

### GALEX

- **GALEX\_Objid**: GALEX object identification number
- **GALEX\_RA**: GALEX RA (J2000)
- **GALEX\_Dec**: GALEX Dec (J2000)
- **NUV\_poserr**: GALEX NUV positional error (arcsec)
- **FUV\_poserr**: GALEX FUV positional error (arcsec)
- **GALEX\_Rel**: MLE reliability of GALEX match to X-ray source
- **GALEX\_Dist**: Distance between X-ray and GALEX source (arcsec)
80 \texttt{NUV\_mag}: GALEX NUV mag
81 \texttt{NUV\_magerr}: GALEX NUV error
82 \texttt{FUV\_mag}: GALEX FUV mag
83 \texttt{FUV\_magerr}: GALEX FUV error
84 \texttt{FIRST Name}: IAU Name of FIRST counterpart
85 \texttt{FIRST\_RA}: FIRST RA (J2000)
86 \texttt{FIRST\_Dec}: FIRST Dec (J2000)
87 \texttt{FIRST\_Dist}: Distance between X-ray and FIRST source (arcsec)
88 \texttt{FIRST\_Flux}: FIRST 5 GHz Flux Density (Jy)
89 \texttt{FIRST\_err}: FIRST 5 GHz Flux Density error (Jy)