AEGIS-X: THE CHANDRA DEEP SURVEY OF THE EXTENDED GROTH STRIP

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Received 2008 April 30; accepted 2008 September 5; published 2008 December 23

ABSTRACT

We present the AEGIS-X survey, a series of deep Chandra ACIS-I observations of the Extended Groth Strip. The survey comprises pointings at eight separate positions, each with nominal exposure of 200 ks, covering a total area of approximately 0.67 deg2 in a strip of length 2 degrees. We describe in detail an updated version of our data reduction and point-source-detection algorithms used to analyze these data. A total of 1325 bandmerged sources have been found to a Poisson probability limit of 4 × 10−6, with limiting fluxes of 5.3 × 10−17 erg cm−2 s−1 in the soft (0.5–2 keV) band and 3.8 × 10−16 erg cm−2 s−1 in the hard (2–10 keV) band. We present simulations verifying the validity of our source-detection procedure and showing a very small, < 1.5%, contamination rate from spurious sources. Optical/NIR counterparts have been identified from the DEEP2, CFHTLS, and Spitzer/Infrared Array Camera (IRAC) surveys of the same region. Using a likelihood ratio method, we find optical counterparts for 76% of our sources, complete to $R_{AB} = 24.1$, and, of the 66% of the sources that have IRAC coverage, 94% have a counterpart to a limit of 0.9 μJy at 3.6 μm ($m_{AB} = 23.8$). After accounting for (small) positional offsets in the eight Chandra fields, the astrometric accuracy of Chandra positions is found to be 0′′.8 rms; however, this number depends both on the off-axis angle and the number of detected counts for a given source. All data products described in this paper are made available via a public Web site.

Key words: galaxies: active – galaxies: nuclei – surveys – X-rays: galaxies

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

There is intense current interest in the formation of galaxies, the history of star formation and accretion power in the universe, and the inter-relations between these phenomena. This has motivated the investment of major observational resources in obtaining images and spectroscopy in various areas of the sky. These multi-wavelength surveys cover a wide range of areas, depths, angular resolutions, and wavebands, ranging from very deep “pencil” beam surveys in small areas of the sky to wider surveys at shallower depths.

Surveys at X-ray wavelengths provide an important component of the multi-wavelength arsenal, primarily because of the efficiency and sensitivity of X-ray emission in selecting active galactic nuclei (AGNs). There is apparently a strong relationship between AGNs and their host galaxy bulges (e.g. Ferrarese & Merritt 2000; Gebhardt et al. 2000), so studying the growth of supermassive black holes in the context of the evolution of their host galaxies is likely to be a fruitful area of exploration. X-ray surveys also enable an estimate of the history of accretion power in the universe and the origin of the X-ray background (e.g. Brandt & Hasinger 2005).

The deepest X-ray surveys in existence are the Chandra Deep Fields North and South (hereafter the CDF-N and CDF-S, respectively), each covering an area of ~ 0.1 deg2 to nominal depths of ~ 2–3 × 10−17 erg cm−2 s−1 (Alexander et al. 2003; Luo et al. 2008). The widest surveys to resolve a significant fraction of the X-ray background cover of order 10 deg2, but to much shallower (by a factor of ~ 100) depths (e.g. XBootes: Murray et al. 2005; Kenter et al. 2005; XMM-LSS: Pierre et al. 2004). The major advantage of ultradeep surveys is that they are able to probe into the distant universe, to detect “typical” objects at high redshift. On the other hand, larger areas are required to sample significant large-scale structures in the universe and hence determine the relationship between galaxy evolution and local environmental density. Moreover, larger area surveys are able to sample and find unusual, rare objects. For a complete picture, it is clearly also necessary to explore the parameter space in between the ultradeep and ultrawide surveys.

Motivated by this, we have obtained deep X-ray observations using the Chandra X-ray observatory (CXO) in a region of sky of area ~ 0.5 deg2 known as the Extended Groth Strip (EGS), covering the energy range 0.5–7 keV. Extensive multi-wavelength data in this region have been obtained as part of the “AEGIS” project (Davis et al. 2007), making it one of the premier datasets to study the co-evolution of black hole accretion and galaxy formation. The purpose of the present paper is to describe the X-ray dataset and reduction, and present a catalog of point sources derived from the Chandra X-ray survey, which we designate AEGIS-X.

The structure of the paper is as follows. In Section 2 we describe the data and reduction, including the method used to calculate the Chandra point-spread function (PSF). Detailed descriptions of our source-detection and photometry procedures are given in Section 3. In Section 4 the results of the source detection and analysis are presented. In
Section 5 the optical and infrared counterparts to the X-ray sources are provided, and in Section 6 the conclusions are given.

2. OBSERVATIONS AND DATA REDUCTION

The data used in this paper were obtained during two Chandra observation cycles. An initial Chandra observation in the EGS region was taken in 2002 August during Cycle 3. These observations of the “Groth–Westphal Strip” (GWS) region have been reported by Nandra et al. (2005, hereafter N05). The majority of the AEGIS-X data were obtained over the period 2005 March–December as part of Chandra Cycle 6. We analyze all the AEGIS-X data here in a uniform fashion. All the observations were taken using the ACIS-I instrument without any grating in place. The S2 and S3 chips of the ACIS-S array were also sometimes operating during the observations, but as these are far off-axis we do not consider the data further. Details of the Chandra observations are shown in Table 1.

2.1. Data Reduction

The data reduction was performed using the CIAO data analysis software version 3.3. Basic data reduction proceeded in a manner similar to that described by N05.

Initially, each observation ID (obsID) was analyzed separately. We first corrected the raw (level 1) event files for any known aspect offsets. Hot pixels and cosmic ray afterglows were removed using the CIAO acis_run_hotpix task for EGS observations 1–7, which were taken in vfaint mode. Application of this task to the EGS-8 data (i.e. the original GWS data), which were taken in faint mode, resulted in images with a large number of apparently spurious sources, which we identified post hoc due to the anomalously low optical/Infrared Array Camera (IRAC) identification rate in this field. Application of the older afterglow removal tool acis_detect_afterglow yielded source numbers and identification rate similar to the other fields. This suggests that the newer CIAO algorithm fails to identify some afterglows and/or hot pixels in the faint mode data. We therefore adopted the acis_detect_afterglow algorithm for the EGS-8 field.

To produce a level 2 (screened) event file we applied the charge-transfer inefficiency (CTI) and time-dependent gain correction, removed the ACIS pixel randomization, and applied pulse-height analyzer randomization, as recommended. In the case of the faint mode data (EGS-1–7) we also applied the ACIS particle background cleaning algorithm.

To identify periods of anomalously high background, which would hamper efficient source detection, we created light curves in the 0.5–7 keV band (excluding sources detected using the celldetect algorithm) with a bin size of 50 s. Background flares were identified using the procedure described by Nandra et al. (2007), whereby a quiescent background level is determined by calculating the count rate limit at which the excess variance of the background light curve is equal to zero. For our Chandra ACIS data, we excluded times when the background count rate exceeded 1.4 times this limit (see Nandra et al. (2007), who used 2 times the limit for XMM-Newton EPIC-pn background cleaning). This procedure was found to be adequate in most cases but some residual background flares not identified by this method were removed manually. One observation, obsID 4365 in field EGS-8, exhibited a ~25 ks period of elevated, but relatively stable and well-behaved, background which would be excluded using the filtering criteria described above. As described by N05, the inclusion of this ~ 25 ks increases the sensitivity of the observation to point sources and therefore has not been filtered from the dataset for this work.

From the cleaned level 2 event file, we created images in four energy bands which we designate full band (FB; 0.5–7 keV), soft band (SB; 0.5–2 keV), hard band (HB; 2–7 keV), and ultrahard band (UB; 4–7 keV). We used the standard CIAO procedure (merge_all) to produce exposure maps for each obsID. These account fully for the telescope and instrument efficiencies, as well as the chip gaps and dithering during the observation. The efficiencies are also a function of photon energy, so creating the exposure maps requires an assumption about the energy distribution of the detected photons, i.e., the source spectrum. N05 calculated these exposure maps at a single energy representative of the detected photons in each band. Following this procedure through to the source photometry stage indicated that these exposure maps produced by this method resulted in HB fluxes that were systematically low. We verified this using MARX simulations (see Section 4.4), inputting synthetic sources of known flux and running through the entire source-detection and photometry procedure. Small systematic flux underestimations were also found for other bands, but the HB suffered the most severe problem, at the ~20% level. In part, this may be due to an inconsistency between the single energy exposure maps, and the $\Gamma = 1.4$ spectrum used to convert counts to flux (see Section 3.3). Switching to a weighted exposure map based on a $\Gamma = 1.4$ spectrum solved the flux problem, and we adopted this for the calculation of all exposure maps.

As already discussed, and listed in Table 1, each field typically comprises several obsIDs and, furthermore, the obsIDs from any given field can overlap the others. It is impractical to perform the analysis for the whole EGS field, as the resulting images would be too large when made at native 0.5 arcsec resolution. We therefore defined a total of eight regions (Figure 1), one for each field, which we used to create images and perform source detection, eventually merging the source catalogs from these regions.

The field regions were defined based on the limits in sky coordinates (X, Y) of the first obsID with a boundary of 20 pixels in all directions. For example, for EGS-1 the field region is defined by the maximum and minimum sky coordinates for obsID 5841, plus or minus 20 pixels in both X and Y directions. We then identified all other obsIDs which overlap with this field box, regardless of whether they are nominally part of that field (e.g. we would combine overlapping data from EGS-2 with EGS-1 where it exists). The exception to this is that we did not combine overlapping data with the three observations that comprise EGS-8 with the adjoining fields (EGS-5 and EGS-6) due to the unfavorable combination of small and large off-axis angle (OAA) data and therefore data with significantly different PSF sizes. Source-detection tests performed when combining data in this way resulted in fewer detections compared to considering the EGS-8 data alone. For each overlapping obsID identified we registered the co-ordinates relative to the first observation in the stack using the acis_align_events task. This performs a source detection using the CIAO celldetect algorithm, at a 3$\sigma$ limit, and uses the centroids to the relatively bright sources so identified to realign the sky coordinates of the images. We only performed this realignment in cases where the algorithm detects at least four such sources. Following the realignment we created a merged event file covering the defined
field region, and images in the soft, full, hard, and ultrahard bands.

An exposure map for the field region was created by summing the exposure maps of the individual obsIDs contributing to the stack, which had been created previously. A plot of the effective exposure versus survey area is shown in Figure 2, comparing \textit{AEGIS-X} to the CDFs. This shows the large increase in area for moderately deep exposures (100–200 ks) afforded by our survey.

The final products of this basic data reduction are therefore the eight event files corresponding to each field EGS-1 to EGS-8, and the corresponding images and exposure maps in the four analysis bands. These images are of manageable size to perform source detection. They also overlap, which helps avoid edge effects in the source detection, but means we must subsequently delete duplicate sources detected in more than one nominal field.

2.2. Point-Spread Functions

To determine accurately the significance and flux of our sources requires a good estimate of the PSF. In the case of \textit{Chandra ACIS} data this depends on the position on the detector
and the energy. Finding previous methods for estimating the Chandra PSF for use in surveys to be unsatisfactory, either because they are not sufficiently accurate (in the case of the CIAO task \texttt{mkpsf}) or because they are prohibitively slow (in the case of ChaRT, the Chandra ray-tracer simulator) we decided to develop our own procedure for calculating the PSF. The most important difference in the analysis of the data in this paper compared to that described by N05 is the use of the new calculations of the PSF.

N05 used the CIAO task \texttt{mkpsf} to estimate the PSF, which calculates a PSF image based on a look-up table based on calculations using the Chandra Ray Tracer PSF simulator ChaRT (Carter et al. 2003). ChaRT simulates photons passing through the best available model of the High-Resolution Mirror Assembly (HRMA), based on extensive pre-launch testing (Jerius et al. 1995), which includes details of the support structures, stray light baffles, and an independent model of each of the mirror segments, and thus provides the best modeling of the PSF for any energy or position in the focal (detector) plane. The available ChaRT-generated library files for \texttt{mkpsf} cover a relatively small number of positions and energies, and the tool must therefore interpolate to generate the necessary PSFs. In addition, for large OAs the PSF images created by \texttt{mkpsf} have the edges clipped, as the PSF can become larger than the generated image.

Therefore, we have taken an alternative approach, and calculated the PSF using the MARX simulator (Wise et al. 2003). MARX is the detector simulator, but is also able to simulate photons passing through a simplified version of the ChaRT HRMA model. In particular, the MARX HRMA model does not include the physical support structure and thus PSFs generated by MARX lack some of the complicated substructure seen in the ChaRT PSFs. However, knowledge of the detailed structure within the PSF is not needed for our point source-detection and photometry methods. We only require an aperture which contains a particular Enclosed Energy Fraction (EEF), and thus the simplified mirror model is sufficient for our needs, as well as requiring less computer processing time.

We have generated look-up tables of the PSF for a range of EEFs over a fine, evenly spaced grid (10 pixel spacing) covering the ACIS-I detector. At each position, an image of the PSF was generated with MARX for a monochromatic source initially of energy 1 keV (representative of our soft band), using 200,000 input rays. The effects of quantum efficiency and the filter transmissions were turned off, as these properties do not affect the PSF, thus maximizing the number of detected photons for a given number of input rays, improving the counting statistics in the PSF image without requiring additional ray traces and longer processing time. At each position, counts were extracted within elliptical apertures (found to best describe the overall

Figure 1. Mosaic full band image of the EGS showing the location and overlap of the eight analysis fields. The EGS-8 field is the original “Groth–Westphal Strip” data described by N05. (A color version of this figure is available in the online journal.)
3. SOURCE DETECTION AND PHOTOMETRY

The point-source catalog was created using an updated version of the source-detection algorithm described by N05 and Laird et al. (2006). Briefly, for the AEGIS-X data, candidate sources were initially identified in each individual field in a number of different energy ranges, their significance computed, and a threshold applied. The sources considered significant were then band-merged, and photometry performed to estimate the fluxes in several energy ranges. Finally, the source catalogs for the individual (overlapping) pointings were merged to remove duplicate sources for the final catalog. These steps are described in detail below.

3.1. Source Detection

The detection algorithm described by N05 involves pre-detection at a low significance threshold followed by aperture extraction of the counts to determine the source significance. The pre-detection is performed using the CIAO wavelet-detection algorithm wavdetect, run on the unbinned, stacked images, at wavelet scales of 1, $\sqrt{2}$, 2, $2\sqrt{2}$, 4, $4\sqrt{2}$, 8, $8\sqrt{2}$, and 16 pixels. Only positions with at least 10% of the maximum field exposure were considered, and the procedure is run at a significance threshold of $10^{-4}$ on images in all four bands. The minimum exposure requirement means that in practice our source catalog will not cover the full 0.64 deg$^2$ of the survey: the least sensitive 3.2% of the total area is excluded. The chosen low threshold for wavdetect is likely to result in a large fraction of spurious sources, but very few real sources should be missed. To determine the source significance, we first calculated the 70% EEF PSFs for the stacked image by exposure weighting the individual PSFs from each individual exposure in the stack as described above.

Using the 70% EEF PSF (determined a priori to be the most efficient radius for source detection) we extracted the total counts for each candidate source, and the effective exposure, the latter being the value of the exposure map averaged over all the pixels in the extraction region. Background counts were determined by first masking the image to remove pixels within the 95% EEF of each candidate wavdetect source. We then extracted background counts from an annulus with an inner radius equal to 1.5 times the 95% EEF radius for the source, and an outer radius 100 pixels more than this. An average exposure map value was calculated for this background area also. The counts in the background area were then scaled to the source region by the ratio of the source and background areas, and the ratio of source and background average exposure.

For each candidate source in each energy band, the Poisson probability that the total counts in the source region would be observed based on the expected background counts was then calculated. Following N05, we adopted a significance of $4 \times 10^{-6}$. Typically, when run at a significance of $10^{-4}$ wavdetect identifies 400–500 candidate sources in each AEGIS-X field, but more than half of these are found to be insignificant—and hence probably background fluctuations—when we perform the aperture extraction and Poisson probability calculations. Because we initially masked out all the wavdetect candidate sources we may therefore have incorrectly masked out the largest positive background fluctuations, leading to an underestimate of the true background level. For this reason we perform a second pass of the source detection, masking out only the sources with Poisson probability $< 4 \times 10^{-6}$ when calculating the background. We then recompute these probabilities with the new background shape of the PSF) with increasing semi-major axis. For each value of the semi-major axis, we calculated the semi-minor axis and orientation angle of the ellipse from the moments of all counts within a circle of radius equal to the semi-major axis. We calculated the EEF for each of the sets of elliptical apertures, and used interpolation to calculate the ellipse parameters for an aperture containing a particular EEF (specifically 50%, 60%, 70%, 80%, 90%, and 95%). The total counts (for normalization of the EEF) were taken from the entire area of the detector.

When sources fell close to the edge of the detector chips or the chip gaps, MARX was altered to shift the nominal position of the detector in the focal plane by around 100 pixels so the PSF was fully sampled. The ellipse parameters for the desired EEFs were stored in look-up tables, providing a very fast method of determining the PSF, using the closest grid position. The PSF varies little on our sampling scale of 10 pixels, so we do not need to interpolate. The procedure was repeated using representative monochromatic energies for each of our energy bands (FB: 2.5 keV; HB: 4 keV; UB: 5.5 keV).

The PSF is defined at a position on the detector (fixed relative to the mirror). However, our X-ray data are the result of a number of observations (obsIDs) with different orientations and pointing directions, merged to create images with the maximum possible exposure. The source detection and photometry described below requires extraction of counts using a single, circular aperture from stacked images which have different PSFs. We therefore calculated exposure-weighted PSFs for each candidate source in the merged images. The position in each of the constituent obsIDs was found, and in each obsID the average value of the exposure map at that position (extracted over approximately 80 surrounding pixels) was calculated, and the PSF was retrieved from the MARX table. Each of the MARX PSFs were converted from ellipses to circles with a radius equal to the square root of the product of the major and minor ellipse axes. For each candidate source the PSFs were then combined, weighting each by the ratio of exposure in a particular obsID to the exposure in the merged image. This was repeated for each energy band.
estimates and reaply the threshold. This second calculation of the Poisson probability is a refinement of the method described by N05 and Laird et al. (2006). Technically further iterations of this kind could be applied but in practice there is negligible difference in the background estimates after two iterations.

When run at low thresholds, such as we have used for the seed catalog, wavdetect sometimes detects the same source twice, particularly at larger OAA’s where the counts are spread out over a wide area. Visually inspecting the images it is clear that only one source is present. During the source-detection phase, we therefore check for sources that are separated by less than 5 pixels. If there are any, then we remove from the list the source position with fewer counts in the 70% EEF area. There are a total of four such cases in AEGIS-X.

3.2. Band Merging

Thus far, the source-detection procedure has been carried out separately for the soft, full, hard, and ultrahard band images. While it is possible that a source will be detected in just one of these bands, in practice the majority of course are detected in several, necessitating a band-merging procedure to produce a single source catalog for that field. In practice most objects are detected in the full band, so we matched the soft, hard, and ultrahard band source lists with the full band. The positional accuracy of Chandra depends on the OAA, due to the position dependence of the PSF, so we adopted a variable radius for source matching. The cross-matching tolerances are shown in Table 2, and are based on positional accuracies as determined from source matching. The cross-matching tolerances are shown in dependence of the PSF, so we adopted a variable radius for Chandra.

| OAA (arcmin) | \( r_{\sigma} \) (arcsec) | Tolerance (arcsec) |
|-------------|-----------------|-----------------|
| 0–3         | 0.30            | 1.30            |
| 3–6         | 0.57            | 2.44            |
| 6–9         | 1.13            | 4.79            |
| ≥9          | 1.67            | 7.08            |

Notes.

* Off-axis angle.

b 1σ positional uncertainty determined from MARX simulations (see text).

c Cross-band match tolerance.

As with source detection, photometry was carried out on each of the eight individual EGS fields. For each source in the band-merged catalog we extracted total counts and effective exposure values from the 90% EEF area in each analysis band. Background counts and exposure values were then extracted in these same bands from an image in which the 95% EEF area of all the significantly detected sources (regardless of the band) had been masked out. The background extraction region was defined in the same way as was for the detection (Section 3.1). Background counts were once more scaled based on the ratio of the areas of the source and background cells and the ratio of the average effective exposures in all pixels in the cells. These scaled background counts were then subtracted from the total counts to give the net source count.

To identify sources that were close to each other, and hence possibly have confused photometry, we identified those that were separated by more than the match tolerances given in Table 2 but whose 90% EEF radii overlap. These are flagged in the catalog as having photometry that is likely contaminated by a nearby object. In some cases, the actual position can fall within the 90% EEF radius of the nearby source. In these cases the photometry will be heavily contaminated by the nearby source, and they are flagged as being confused. In such cases the positions may also be highly inaccurate.

We calculated source fluxes and 1σ confidence limits from the detected counts using a Bayesian method that corrects for the Eddington bias (Eddington 1940) and is based on Kraft et al. (1991). This methodology assumes the range of possible source fluxes is a continuous distribution fully described by the observed data and prior knowledge of the physical system. We apply Bayes’ theorem,

\[
P(S|N, B) \propto \mathcal{L}(N|S, B)\pi(S),
\]

where \( P(S|N, B) \) is the posterior distribution function for the source rate, \( S \), \( \mathcal{L}(N|S, B) \) is the Poisson likelihood of obtaining the observed data, \( N \), counts, for a given source rate, \( S \), and background \( B \). Thus,

\[
\mathcal{L}(N|S, B) = \frac{(S + B)^N}{N!}e^{-(S+B)}.
\]

This approach naturally incorporates the contribution of both source and background components to the total observed counts, and thus provides a better description of the nature of faint sources than classical approaches normally employed (e.g. Giacconi et al. 2002; Alexander et al. 2003; Kim et al. 2007). \( \pi(S) \) is the prior probability distribution, and reflects our prior knowledge of the range of possible source fluxes. Kraft et al. (1991) adopted a constant uninformative prior, requiring only that the source flux must be greater than 0. However, the distribution of fluxes of X-ray sources (the log \( N \)–log \( S \)) are found to be well described by a broken power law (Georgakakis et al. 2008). This introduces Eddington bias which affects the classical estimate of source fluxes since a larger number of faint sources are scattered to higher fluxes than vice versa. Thus, the fluxes of faint sources are generally overestimated. We can correct for the Eddington bias with our Bayesian method, by adopting a prior based on the observed log \( N \)–log \( S \) relation. To approximate the log \( N \)–log \( S \), we use a faint end slope of \(-1.5\) and a bright end slope of \(-2.5\) for each of the analysis bands. We use break fluxes for each band as given in Georgakakis.
et al. (2008, Table 2). The best estimate of the source flux is then obtained by finding the mode of the posterior distribution. Differentiating Equation (1) provides an analytic solution for a prior with the power-law slope $\beta$,

$$\hat{S} = \frac{1}{2}(N - B + \beta + \sqrt{(N - B + \beta)^2 + 4B\beta}).$$

(3)

This expression is easily extended to the case of a broken power law. An additional condition for the existence of a solution is introduced,

$$(N - B + \beta)^2 \geq -4B\beta.$$

(4)

When there is no solution, we only quote upper limits on the source fluxes.

For the Bayesian approach, confidence limits are obtained by integrating the posterior distribution,

$$CL = \int_{S_L}^{S_H} \mathcal{L}(N|S, B)\pi(S) \, dS$$

(5)

where CL is a given confidence level and $K$ is a normalization constant. For a faint-end slope of $\beta_1 = -1.5$ the posterior distribution diverges at the faintest fluxes. Extending the power-law distribution to the faintest fluxes is clearly unphysical, and makes normalization impossible. We thus set a lower limit to the possible source fluxes which is 10 times fainter than the detection limit at the position of each source, given the background. Following Kraft et al. (1991), we adopt Highest Posterior Density intervals, which minimize the size of the confidence interval for the given confidence level (68%), and thus sets the tightest limits on the source flux. These are calculated by numerical integration of Equation (5).

We use this method to calculate the fluxes of all sources in each of the four bands, regardless of their Poisson probability or net counts. While many sources are not detected in all four analysis bands, we can nonetheless often determine reasonably reliable fluxes in those undetected bands. Effective on-axis source count rates were calculated by dividing the net counts with the average value of the exposure map, and aperture correcting. Count rates were converted to fluxes using a $\Gamma = 1.4$ spectrum with Galactic $N_H$ of $1.3 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). The count rates in the full, hard, and ultrahard bands were also extrapolated to the standard bands: 0.5–10, 2–10, and 5–10 keV, respectively.

For comparison, we also calculated fluxes using a classical method, with the 1$\sigma$ confidence ranges on the detected counts determined according to the prescription of Gehrels (1986). In Figure 3 we compare the Bayesian and classical methods for calculating fluxes, for full band sources. For bright sources, $f_{0.5–10\text{ keV}} \geq 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, the fluxes and errors from both methods agree well. However, the fluxes of the faintest sources do not agree because the classical method fails to correct for the Eddington bias or accurately describe the errors. In such cases the classical method can overpredict the fluxes by up to a factor of 2.

3.4. Hardness Ratios (HRs)

HRs were calculated using a Bayesian approach, following Park et al. (2006). Their method models the detected counts as a Poisson distribution and gives error bars and reliable HRs for sources with both low and high counts. To calculate the HRs with the Bayesian approach we use the BEHR$^9$ package (ver. 11-08-2007, Park et al. 2006). For this we use a flat, non-informative prior and use the Gaussian quadrature method for sources with less than 20 net counts in either the soft or hard bands, and the Gibbs sampler method for all other sources. Effective area corrections to on-axis values are input to BEHR to allow on-axis HRs to be calculated and we use the mean of the posterior probability distribution as the best estimate for the HR (Park et al. 2006).

For comparison, we also calculated HRs using the classical method: $HR = (H - S)/(H + S)$, where $H$ and $S$ are simply hard and soft band net counts, respectively, corrected to on-axis values. Where a source has only upper limits in the soft or hard bands, the HR is designated as $+1$ and $-1$, respectively. Figure 4 compares the two methods of calculating HR. There is good agreement for the bright, highly significant sources, but for weak sources the two methods disagree, particularly at low and high HR values, confirming the results of Park et al. (2006) and Kim et al. (2007).

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9 See http://hea-www.harvard.edu/AstroStat/BEHR/
For a number of applications, one needs to know the flux sensitivity of the images as a function of position and energy band. We have calculated sensitivity maps, and hence also the area of the AEGIS-X survey as a function of flux, using the method described by Georgakakis et al. (2008). This accurately estimates the probability of detecting a source with a given X-ray flux accounting for observational effects, flux estimation biases, and the fraction of spurious sources expected in any source catalog. The backbone of the method is the Poisson probability distribution. For a detection cell with local background, \( B \), one can estimate the minimum integer number of total counts, \( L \), for which the Poisson probability that fluctuations of the background produce at least \( L \) counts is less than the adopted threshold for source detection, \( 4 \times 10^{-6} \). Repeating this exercise for different cells across the image one can determine \( L \) as a function of position on the detector. The 2D image of \( L \) is the sensitivity map. The sensitivity map determined in this way does not require any assumptions on the spectral shape of the source.

A useful 1D representation of the sensitivity map is the total sensitivity curve. The sensitivity map determined in this way does not require any assumptions on the spectral shape of the source. For a source with flux \( f_X \) and a given spectral shape \( \Gamma \) (in this paper) we determine the probability of detection in a cell with mean background \( B \) and detection limit \( L \). The total observed counts in the cell are \( T = B + S \), where \( S \) is the mean expected source contribution. In practice this depends on the observation exposure time, the vignetting of the field at the position of the cell, and the fraction of the total source counts in the cell because of the PSF size. The probability that \( T \) exceeds \( L \) is given by the cumulative Poisson probability.

Again, for comparison purposes, we have also calculated the sensitivity maps using a “classical” method (as, e.g. N05), whereby we assign a single limiting flux to each detection cell. The sensitivity curves in different energy bands estimated using the Georgakakis et al. (2008) and classical methods are shown in Figure 5. In the classical method there is a limiting flux below which the sensitivity drops to zero. In contrast, in the Georgakakis et al. (2008) method, at faint fluxes as \( S \rightarrow 0 \) the Poisson probability converges to \( P_{\text{thresh}} = 4 \times 10^{-6} \), because this is the finite probability of a random background fluctuation above the limit \( L \).

### 3.5. Sensitivity Maps

To produce the final catalog we need both to remove duplicate sources detected in more than one of the (overlapping) fields, and to register all the images to the same astrometric frame. To do so, we first matched the X-ray catalogs to the DEEP2 optical photometry catalog (Coil et al. 2004) and the median R.A. and decl. offsets were calculated. The X-ray positions were shifted to be in agreement with the DEEP2 images (i.e. the SDSS frame; Coil et al. 2004) using the offsets given in Table 3. The source lists were then combined by finding the closest source within a match radius of 5″. Typically the offsets were much smaller than this (see Section 4.4); however, as sources are matched only between individual fields and not within them there is no danger of close sources being erroneously combined. We visually compared the combined source list to the individual field source lists to confirm this. Where a source is detected in more than one field, we quote the source properties

| Field  | \( \Delta \) R.A. (arcsec) | \( \Delta \) Decl. (arcsec) |
|--------|---------------------------|---------------------------|
| EGS-1  | -0.081                    | 0.046                     |
| EGS-2  | -0.031                    | 0.060                     |
| EGS-3  | 0.025                     | 0.048                     |
| EGS-4  | -0.151                    | 0.086                     |
| EGS-5  | -0.197                    | -0.004                    |
| EGS-6  | -0.068                    | -0.051                    |
| EGS-7  | -0.102                    | -0.002                    |
| EGS-8  | -0.072                    | 0.059                     |
(e.g., counts, probabilities, fluxes) for the field in which the source has the smaller OAA relative to the field center. Usually the source properties will be very similar in the two overlapping frames in which it is detected, but can differ subtly as, e.g., the backgrounds will in general be different. The original detected field can be identified by the “Field_ID” tag in the source catalog. The final catalog was ordered and numbered according to increasing R.A.

Once double sources are removed, there is a total of 1325 distinct sources in the final catalog (Table 9). Details of how many sources are detected in each individual band are given in Table 4 and a summary of the number of sources detected in one band but not another is given in Table 5. A large number of sources are detected at \( p < 4 \times 10^{-6} \) in just one band, specifically, 115, 85, 14, and 2 in the full, soft, hard, and ultrahard bands, respectively. The brightest significant source in the catalog has a total of 4290.5 net counts in the FB and the faintest has 4.2 net counts.

### 4.1. Flux Limit

Using the sensitivity curves in Figure 5 we determine the limiting fluxes in each band, defined as the flux to which at least 1% of the survey area is sensitive, to be \( 2.37 \times 10^{-16} \) (FB; 0.5–10 keV), \( 5.31 \times 10^{-17} \) (SB; 0.5–2 keV), \( 3.76 \times 10^{-16} \) (HB; 2–10 keV), and \( 6.24 \times 10^{-16} \) erg cm\(^{-2}\) s\(^{-1}\) (UB; 5–10 keV). The total area of the survey is 0.64 deg\(^2\). Using classical sensitivity curves which do not correct for the Eddington bias, as in N05, gives limiting fluxes that are approximately a factor of 2 greater. Because the sensitivity varies dramatically across the images, we also give the flux limits corresponding to 50% and 90% completeness in Table 6. Figure 6 shows the distribution of X-ray flux in each of the four bands. The fluxes cover a range of over 3 dex, with \( \sim 50\% \) of detected soft and hard band sources having fluxes of less than \( 9.7 \times 10^{-16} \) and \( 4.5 \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\), respectively.

### 4.2. Comparison With wavdetect

The standard procedure for source detection with Chandra ACIS data is the wavelet-based algorithm wavdetect (Freeman et al. 2002). In order to compare our detection method, and verify that it is correctly identifying significant sources, we also performed source detection using the CIAO wavdetect algorithm in each of the eight fields. Running wavdetect with a detection threshold of \( 10^{-7} \), commonly used for ACIS-I surveys (e.g., Alexander et al. 2003; Yang et al. 2004; Wang et al. 2007), and creating a band-merged catalog for the whole of the EGS, we found that the total number of independent sources detected was 1258, compared to 1325 using our method, and less sources were detected in every band (Table 4).

Matching the two catalogs showed that there were 1208 sources in common. There were 59 sources that were only in the wavdetect catalog and 122 sources that were only in the AEGIS-X catalog. To assess the likelihood of these sources being real we searched for optical and infrared (IR) counterparts in the DEEP2 and Spitzer/IRAC photometry catalogs covering the EGS (see Section 5 for details of the optical and IR data and the method for identifying secure counterparts). Real X-ray sources are likely to have a higher counterpart identification rate. We find secure optical counterparts for 59% of the AEGIS-X-only sources, compared to an optical identification rate of 47% for the wavdetect-only sources. Of the 73 AEGIS-X-only sources that are covered by the Spitzer/IRAC

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**Table 4**

| Method | \( P_{\text{thresh}} \) | FB\(^a\) | SB\(^a\) | HB\(^a\) | UB\(^a\) | Merged \( N \) |
|--------|-----------------|-------|-------|-------|-------|----------|
| This work | \( 4 \times 10^{-6} \) | 1221 | 1032 | 741 | 350 | 1325 |
| wavdetect | \( 1 \times 10^{-7} \) | 1160 | 968 | 696 | 311 | 1258 |

**Note.** \( a \) FB, full band (0.5–7 keV); SB, soft band (0.5–2 keV); HB, hard band (2–7 keV); UB, ultrahard band (4–7 keV).

**Table 5**

| Band (keV) | Non-Detection Band |
|-----------|--------------------|
|           | Full | Soft | Hard | Ultrahard |
| Full (0.5–7) | \( \ldots \) | 274 | 497 | 876 |
| Soft (0.5–2) | 85 | \( \ldots \) | 466 | 748 |
| Hard (2–7) | 17 | 175 | \( \ldots \) | 396 |
| Ultrahard (4–7) | 5 | 66 | 5 | \( \ldots \) |

**Table 6**

| Band | Completeness limit \( a \) |
|------|----------------------------|
|      | 1% \(^b\) | 50% \(^b\) | 90% \(^b\) |
| Full | 2.37 | 13.03 | 40.27 |
| Soft | 0.53 | 3.35 | 11.09 |
| Hard | 3.76 | 20.65 | 62.37 |
| Ultrahard | 6.24 | 38.50 | 124.45 |

**Notes.**

\( a \) Flux to which 1%, 50%, and 90% of the survey area is complete.  
\( b \) Fluxes are in units of \( 10^{-16} \) erg cm\(^{-2}\) s\(^{-1}\).
data 88% have secure IR counterparts, compared to 40% of the 43 wavdetect-only sources covered by the data. Therefore, while some fraction of the 59 X-ray sources that are in the wavdetect catalog, but have been missed by our source detection, may indeed be real, we can be confident that the extra sources included in the AEGIS-X catalog are at least more likely to be real X-ray sources than those that were missed.

4.3. Comparison With N05 GWS Analysis

The three obsIDs that constitute EGS-8 were previously reduced and analyzed as part of the “Groth–Westphal Strip” survey and a point source catalog was presented by N05. In this more recent reduction and analysis of the data there are a number of differences in the source-detection results, compared to the N05 results. As was stated in Section 2.1, this field was analyzed independently of the rest of the EGS data and therefore includes the same data as in our previous work. In both analyses 158 independent sources were detected in the field, however the IDs of all of the sources are not the same. There are 10 new AEGIS-X sources that were not detected in N05 and nine sources in the N05 GWS catalog that are not included in the AEGIS-X catalog (Table 7). One further GWS source (c13) was not detected in EGS-8 but was detected in EGS-6, which overlaps with the field, and is therefore included in the final source list. The high optical identification rate of the sources, as determined by Georgakakis et al. (2006), suggests that the majority of the nine sources are probably real. However, in order to maintain a well-controlled sample we have not included them in our final AEGIS-X catalog.

There are several small differences in our reduction and analysis that could lead to the different source lists. The EGS-8 data used in this work have a longer total exposure (∼7 ks) and the PSFs were calculated using a different method and are on average 7% larger than before. However, the probable main reason that the sources are not detected in this analysis is the refinement of our source-detection method from the method used by N05. The second pass of source detection described in Section 3.1 leads to 25% higher background levels than in N05 and therefore faint sources with Poisson probabilities close to the detection threshold, such as those in Table 7, will no longer pass the detection criteria. The Poisson probabilities of the nine N05 sources using the new higher background are shown in Table 7; several sources were just below our detection criteria for being included in the AEGIS-X catalog.

4.4. Astrometric Accuracy

The astrometric accuracy of the Chandra positions was estimated using MARX to generate simulated fields. Synthetic point sources were added to the simulated images adopting a single power-law log N–log S distribution with parameters tuned to reproduce the faint end of the 2–10 keV X-ray number counts. The slope of the differential counts was set to β = −1.58 and the normalization is fixed so that there are 7000 sources per square degree brighter than \( f_X (2–10 \text{ keV}) = 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \), i.e. similar to the observed density of X-ray sources (Kim et al. 2007; Georgakakis et al. 2008). This choice of parameters will overpredict the number of bright sources but for the purposes of determining the positional error this is irrelevant. We adopt an X-ray spectrum with \( \Gamma = 1.4 \) and a total exposure time of 200 ks. Simulated ACIS-I event files are constructed by randomly placing within the Chandra field of view point sources with fluxes in the range \( f_X (2–10 \text{ keV}) = 5 \times 10^{-17} \text{ to } 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \). MARX does not simulate the Chandra background. This is added to the simulated images using the quiescent background event files produced by the ACIS calibration team using blank sky observations. A total of 10 such simulations was performed. Each simulated field was ran through the entire source-detection procedure. In each simulation, there are on average about 180 sources with detection probability \( < 4 \times 10^{-6} \) in at least one of the four analysis bands. The detected source positions were then compared to the input positions of the sources in the simulation. It should be noted that the astrometric accuracy determined this way, using simple, single field images, accounts only for statistical errors and does not take into account any systematic errors that may be present using the more complex AEGIS-X data.

As expected, the positional accuracy depends on both the OAA, and the number of source counts. However, the simulations showed only a mild dependence on source counts and therefore for the purpose of cross-band matching we chose radii that depended only on OAA. The estimated 1σ positional accuracies are shown in the second column of Table 2, averaged over all source counts.

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**Table 7**

GWS Sources from N05 not Included in the AEGIS-X Catalog

| No5 Cat. No. | R.A. J2000° | Decl. J2000° | \( p_{\text{min}} \, ^{a,b} \) | \( R_{\text{AB}} \, ^{c} \) | Comments^d | \( p_{\text{min}} \, ^{b,d} \) |
|-------------|-------------|-------------|----------------|----------------|-------------|----------------|
| c14         | 14 16 59.26 | +52 34 36.04 | 1.3 \times 10^{-6} | fh             | 25.03       | 5.5 \times 10^{-6} |
| c35         | 14 17 18.89 | +52 27 43.74 | 1.1 \times 10^{-6} | f              | 23.47       | 4.1 \times 10^{-6} |
| c45         | 14 17 25.28 | +52 35 12.08 | 4.0 \times 10^{-6} | f              | > 26.0      | 1.8 \times 10^{-4} |
| c68         | 14 17 39.06 | +52 28 43.78 | 3.2 \times 10^{-7} | fs             | 24.92       | 2.3 \times 10^{-3} |
| c73         | 14 17 42.86 | +52 22 35.21 | 1.9 \times 10^{-8} | fh             | 23.25       | 7.6 \times 10^{-4} |
| c80         | 14 17 47.01 | +52 25 12.07 | 1.2 \times 10^{-6} | fh             | 22.54       | 3.1 \times 10^{-3} |
| c102        | 14 17 56.92 | +52 31 18.47 | 3.7 \times 10^{-6} | f              | 25.10       | 3.6 \times 10^{-5} |
| c125        | 14 18 08.06 | +52 27 50.36 | 2.4 \times 10^{-6} | f              | > 26.0      | 2.7 \times 10^{-4} |

Notes:

- ^a Values from N05.
- ^b Lowest false detection probability found for the four analysis bands.
- ^c Optical identification from Georgakakis et al. (2006).
- ^d Values from this work.
The absolute astrometric accuracy of the Chandra positions in the AEGIS-X catalog were verified by matching the AEGIS-X sources to the DEEP2 optical data from the AEGIS project (see Section 5.1 for details), for which the absolute positional uncertainty is 0.2′′ rms (A. L. Coil, 2007, private communication). As described above, to combine the catalogs from each of the eight fields we first registered the positions to match the astrometric frame of the DEEP2 catalog using the offsets given in Table 3. Matching the final catalog to DEEP2, and considering only secure optical counterparts, we find that the median and rms positional offsets of 868 matched sources are 0.40 and 0.79, respectively. The dependence of the astrometric accuracy on the OAA and source counts is illustrated in Figure 7. We determine the 1σ astrometric accuracy of sources in the AEGIS-X catalog by breaking the sample down into nine bins based on OAA and net counts (Table 8).

### Table 8

| OAA (arcmin) | Net Full Band Counts |
|--------------|----------------------|
|              | $S \leq 50$ (arcsec) | $50 < S \leq 100$ (arcsec) | $S > 100$ (arcsec) |
| 0–4          | 0.56                 | 0.36                        | 0.14                |
| 4–8          | 0.96                 | 0.61                        | 0.44                |
| >8           | 1.33                 | 0.87                        | 0.57                |

The absolute astrometric accuracy of the Chandra positions in the AEGIS-X catalog were verified by matching the AEGIS-X sources to the DEEP2 optical data from the AEGIS project (see Section 5.1 for details), for which the absolute positional uncertainty is 0.2′′ rms (A. L. Coil, 2007, private communication). As described above, to combine the catalogs from each of the eight fields we first registered the positions to match the astrometric frame of the DEEP2 catalog using the offsets given in Table 3. Matching the final catalog to DEEP2, and considering only secure optical counterparts, we find that the median and rms positional offsets of 868 matched sources are 0.40 and 0.79, respectively. The dependence of the astrometric accuracy on the OAA and source counts is illustrated in Figure 7. We determine the 1σ astrometric accuracy of sources in the AEGIS-X catalog by breaking the sample down into nine bins based on OAA and net counts (Table 8).

#### 4.5. False Source Contamination

The number of false sources in our catalog was assessed using the quiescent background event files produced by the ACIS team based on blank sky observations. These event files were used to simulate 20 200 ks ACIS-I blank fields to match our data. The simulated images will give an estimate of the number of statistical spurious sources expected in 200 ks data but will not account for possible systematic spurious sources that may result from the more complex AEGIS-X data with its multiple overlapping observations. Running our full source-detection procedure on the simulated images we find there to be 0.58 spurious sources detected per 200 ks field per band, similar to the 0.5 sources per band estimated by N05. Therefore, we expect there to be a total of no more than 19 spurious sources in our catalog, equivalent to a contamination rate of less than 1.5%.

#### 4.6. Final AEGIS-X Catalog

The final AEGIS-X point source catalog is presented in Tables 9 and 10. Table 9 gives the basic source properties such as source position, source counts, and details of the detection significance. Column 1 gives the source ID and Column 2 gives the field ID, which identifies the individual field in which the source was detected. Sources are listed in order of increasing R.A. Column 3 gives the CXO object name. Columns 4 and 5 are the R.A. and decl. of the X-ray sources, respectively. These coordinates have been shifted to agree with the Sloan Digital Sky Survey (SDSS) reference frame of the DEEP2 images (Table 3). Column 6 is the positional error in arcsec, as detailed above. The source OAA, in arcmin, is given in Column 7. Columns 8–15 give the total source counts ($N$) and background counts ($B$) in the four analysis bands. Counts are given regardless of whether a source was detected in the band. Column 16 lists the bands in which the source is detected with Poisson probability < $4 \times 10^{-6}$, where the bands are full (f), soft (s), hard (h), and ultrahard (uh). Column 17 gives the lowest false detection probability found for the four bands; probabilities lower than $10^{-8}$ are quoted in the table as $10^{-8}$.

Table 10 lists the flux and HR information for the sources. Column 1 again gives the source ID. Columns 2–5 give the fluxes calculated using the Bayesian method described in Section 3.3, which corrects for the Eddington bias. The errors are 1σ values and the limits are 1σ, or 68%, upper limits. In three cases (egs_0367, egs_0457, and egs_0633) sources that were significantly detected in a band had best estimate fluxes of zero, using the Bayesian method. This discrepancy arises due to the different EEFs used for the photometry (90% EEF) and for the detection (70% EEF). In these cases, we use source and background counts corresponding to the 70% EEF area to calculate the fluxes in the detected bands. Columns 6–9 give the observed frame fluxes in the four bands, where the fluxes and errors have been calculated using the classical method. The errors are 1σ values, however here the limits are 99% upper limits. All the fluxes listed are in units of...
10^{-15} \text{ erg cm}^{-2} \text{s}^{-1} and have not been corrected for Galactic or intrinsic source absorption. To correct for Galactic absorption the full and soft band fluxes should be increased by 2% and 4.2%, respectively. The corrections to the hard and ultrahard fluxes are negligible. Columns 10 and 11 give the Bayesian and classical HRs, respectively. The errors for the Bayesian HRs are 1σ. For sources only detected in the full band, and with upper limits in both hard and soft bands, the classical HR cannot be determined and is set to −99. Column 12 is a flag for the quality of the photometry. A flag of “1” indicates the presence of a nearby source that may be contaminating the photometry. A flag of “2” indicates that another source was detected with the 90% EEF and that the photometry is likely heavily contaminated and the source position uncertain (Section 3.3). All other sources have a flag of “0.”

The AEGIS-X source catalog is publicly available in FITS table format at http://astro.imperial.ac.uk/research/aegis/cats.shtml. The FITS version of the catalog contains more information about the sources, such as the Poisson probability, counts, PSF size, and exposure value in each of the bands. Postage stamp images of the sources are also available.

5. OPTICAL AND IR IDENTIFICATIONS

We identify secure optical and IR counterparts to the Chandra X-ray sources using the maximum likelihood (LR) method (Ciliegi et al. 2003, 2005; Brusa et al. 2007). This is the ratio between the probability that a source, at a given distance from the X-ray position and with a given optical or IR magnitude, is the true ID and the probability that this source is a spurious alignment. The LR ratio takes into account the X-ray, optical, or IR positional uncertainty, the background density of optical (or IR) galaxies and the a priori probability of a counterpart with a given magnitude.

For the positional accuracy of the X-ray sources, we adopt a Gaussian distribution with standard deviation estimated as a function of the OAA and total number of counts from the MARX simulations described in Section 4.4. The optical identification is a two-pass procedure. In the first pass, we estimate the a priori probability that an X-ray source has a counterpart of given magnitude in the input catalog (optical or IR). We use a fixed search radius of 2′ to identify the X-ray sources with counterparts in the input catalog. A total of 100 mock catalogs are then constructed by randomizing the source positions of the input catalog and the cross matching is repeated. The magnitude distributions of the counterparts in the mock and the real catalogs are subtracted to determine the magnitude distribution of the real associations. This is then used as a prior in the LR ratio estimation to account for the distribution of X-ray sources in magnitudes and the total expected number of true associations. In the second pass, a search radius of 4′ (equivalent to the 3σ positional uncertainty at large OAA) is adopted to identify all
and is complete to a limiting magnitude of 2004. These data cover almost the entire astrometric accuracy of the photometric catalog is estimated to be 0.7 arcsec. The DEEP2 imaging area and the Chandra imaging area are part of the CFHT Legacy survey10 (CFHTLS). The CFHTLS includes data from five filters: u, g', r', i', and z', and is complete to \( i'_{AB} = 27.0 \). The overlap between the CFHTLS imaging area and the Chandra area is 0.33 deg2, considerably smaller than the overlap with the DEEP2 optical imaging described above. The CFHTLS catalogs we are using are from the T0003 release, in which the astrometry was calculated using the USNO-B1 catalog. The astrometric uncertainty of the CFHTLS catalog is estimated to be about 0.7 arcsec. Details about the data and catalog are given in the TERAPIX pages relevant to that release: http://terapix.iap.fr/article.php?id_article=556.

Using the maximum likelihood method, we search for optical counterparts to the AEGIS-X sources in the DEEP2 survey using the DEEP2 R-selected catalog to estimate the surface density of background optical sources, \( R \) being the deepest band in the DEEP2 survey. The \( i' \) band is the deepest band in the CFHTLS survey so we use the \( i' \)-selected catalog to estimate the surface density of background optical sources for the CFHTLS. For both the DEEP2 and CFHTLS surveys we consider counterparts with \( LR > 0.5 \) as secure, giving a \( \sim 6\% \) contamination rate in both cases.

Of the 1317 AEGIS-X sources that are covered by the DEEP2 survey, which is complete to \( R_{AB} = 24.1 \), we find that 897 have secure \( R \) band counterparts, an optical ID rate of 68.1\%. The deeper CFHTLS data, complete to \( i'_{AB} = 27.0 \), overlap with 703 AEGIS-X sources, and we find that 578 (82.2\%) of them have secure \( i' \) band-selected optical counterparts. Taking into account both catalogs, 1013 of the 1325 AEGIS-X sources have optical counterparts, with 13.95 \( \leq R_{AB} \leq 26.65 \). At the limit to which all of the optical coverage is complete, \( R_{AB} = 24.1 \), we find an optical counterpart rate of 57\%. The optical ID rates found for the AEGIS-X sources are similar to those found for other deep Chandra surveys. For instance, in the deeper CDF-N Barger et al. (2003) found optical counterparts for 85\% of the sources to \( R \leq 26.4 \), with an estimated 15\% contamination rate. Considering only \( R \leq 24.0 \) sources, they found an optical ID rate of 55\%, in agreement with the AEGIS-X findings.

Table 11 gives the results of the optical counterpart analysis. The table lists the \( R \) magnitude for every source with a secure DEEP2 counterpart, along with the offset between the X-ray and DEEP2 source (\( \delta_{opt-X} \)), the LR, and the DEEP2 counterpart ID number. The \( i' \) magnitude, offset between the X-ray and CFHTLS source, LR, and counterpart ID number are also given for every secure CFHTLS counterpart.

Figure 8 shows soft X-ray flux versus \( R \) magnitude for the sample, for all the sources with secure optical counterparts. For X-ray sources with DEEP2 counterparts we use the DEEP2 \( R \) magnitude. For sources not detected in the DEEP2 survey, but securely detected in the CFHTLS then we convert the CFHTLS \( r'_{AB} \) magnitudes to \( R_{AB} \) using

\[
R = r' - 0.0576 - 0.3718[(r' - i') - 0.2589]
\]
Figure 8. 0.5–2 keV flux vs. R magnitude for sources with DEEP2 or CFHTLS counterparts. For X-ray sources with DEEP2 counterparts we plot the DEEP2 magnitudes, for sources not detected in DEEP2 but detected in the CFHTLS then we use CFHTLS $r_{AB}$ converted to $R_{AB}$ (as described in Section 5.1), otherwise we plot the DEEP2 upper limit. Lines of the constant X-ray to optical flux ratio are plotted, according to the relation of Hornschemeier et al. (2001). The symbol shapes and colors are defined by the positions on the $f_X/f_{opt}$ plot as follows: (red squares) $\log(f_X/f_{opt}) > 1$, (black circles) $-1 < \log(f_X/f_{opt}) < 1$, (green inverted triangles) $-2 < \log(f_X/f_{opt}) < -1$, and (blue triangles) $\log(f_X/f_{opt}) < -2$. (A color version of this figure is available in the online journal.)

Figure 9. 0.5–2 keV flux vs. IRAC 3.6 μm magnitudes for sources with secure IRAC counterparts. Lines of the constant X-ray to IR flux ratio are plotted, using the 3.6 μm zero-points given by Reach et al. (2005). (Top) Sources with secure optical counterparts: symbol shapes and colors are the same as Figure 8. (Bottom) Sources without secure optical counterparts. A few bright, saturated stars. Such sources are commented in Table 11. (A color version of this figure is available in the online journal.)

(Branch & Roweis 2007). This transformation is correct for the Bessell et al. (1998) $R$ filter which differs slightly from the CFHT filter used in the DEEP2 survey, but should be correct to within 0.1 mag or less. Upper limits are plotted, where appropriate. The ratio of X-ray to optical flux is a useful diagnostic for determining the nature of X-ray sources. Over several decades in flux classic AGN, both narrow and broad line, exhibit X-ray to optical flux ratios of $-1 < \log(f_X/f_{opt}) < 1$ (e.g. Schmidt et al. 1998; Akiyama et al. 2000; Alexander et al. 2001), while at lower X-ray to optical flux ratios low-luminosity AGN, starburst galaxies, and normal galaxies emerge (e.g. Alexander et al. 2001; Barger et al. 2002). The sources in the AEGIS-X catalog cover over four orders of magnitudes in $f_X$-to-$f_{opt}$ ratio. As expected, the majority of the AEGIS-X sources populate the AGN region of the diagram but a significant number of sources fall within the regions normally populated with starburst or composite star-forming/AGN galaxies ($-2 < \log(f_X/f_{opt}) < -1$; e.g. Bauer et al. 2002; Alexander et al. 2002) and normal galaxies ($\log(f_X/f_{opt}) < -2$; Hornschemeier et al. 2003).

5.2. IRAC Identifications

The majority of the AEGIS field is covered by sensitive Spitzer/IRAC data, described in detail by Barmby et al. (2006, 2008). Briefly, these data cover the whole length of the strip but with a width of only $0^\prime$. Here we consider only the 3.6-μm-selected catalog of Barmby et al. (2008), which has a 50% point source completeness limit of 0.9 μJy at 3.6 μm (or $m_{3.6 \mu m}$ (AB) = 23.8). The astrometric uncertainty of the IRAC catalog is estimated to be $0^\prime 35$. A total of 882 Chandra sources are covered by the Spitzer region. Using the maximum likelihood method, and again considering only matches with LR $> 0.5$, we find that 830 (94.1%) have secure 3.6 μm counterparts.

This cut on LR gives a $\sim 1\%$ spurious counterpart rate. The 94% IRAC ID rate found here is consistent with that found in the 250 ks Extended Chandra Deep Field-South; Cardamone et al. (2008) found IRAC counterparts for 90% of the X-ray sources to an IRAC flux limit of 0.63 μJy at 3.6 μm.

Table 11 lists the 3.6 μm magnitude for each source with a secure IRAC counterpart, along with the offset between the X-ray and IRAC source ($\delta_{RIR}$), the LR, and the IRAC ID from Barmby et al. (2008). Figure 9 shows soft X-ray flux versus 3.6 μm magnitude for the sample, for the sources with an IRAC counterpart. Galaxies identified as classic AGN in Figure 8 (black circles and red squares) occupy the region of the plot defined by $-2 < \log(f_X/f_{IR}) < 0$. The sources in the AEGIS-X catalog cover over three orders of magnitudes in the $f_X$-to-$f_{IR}$ ratio. The AEGIS-X sources without an optical counterpart are on average fainter at 3.6 μm and exhibit a smaller range in the $f_X$-to-$f_{IR}$ ratio than those sources with an optical counterpart.
6. CONCLUSIONS

We have presented a catalog of X-ray point sources from the 0.67 deg$^2$ AEGIS-X survey. Using a detection threshold of Poisson probability $< 4 \times 10^{-6}$ we detected 1325 independent point sources down to on-axis flux limits of $2.37 \times 10^{-16}$ (0.5–10 keV), $5.31 \times 10^{-17}$ (0.5–2 keV), and $3.76 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV). For each source we determine the X-ray flux in four bands (full, soft, hard, and ultrahard) using a Bayesian method that corrects for the Eddington bias, in addition to the standard flux calculation method. Optical and IR counterparts to the X-ray sources were identified from the DEEP2, CFHTLS, and Spitzer/IRAC surveys of the EGS, and the results are presented. We find that 76% and 94% of the AEGIS-X sources have secure optical and IR counterparts, respectively.

A number of analysis methods used in this work were specifically developed for Chandra surveys such as this one. The source catalog was produced using our own source-detection procedure that is described in detail. Simulations verified the validity of this detection procedure and predict a very small, $<1.5\%$, contamination rate from spurious sources. The photometry method employed corrects for the Eddington bias. A method for calculating accurate PSFs for multi-observation datasets, such as the AEGIS-X survey, is also presented. Sensitivity maps and sensitivity curves were made following the new method of Georgakakis et al. (2008), which efficiently and correctly accounts for the observational biases that affect the probability of detecting a source at a given flux.

Finally, all of the data products described in this paper, including reduced event files, images, exposure maps, sensitivity maps, sensitivity curves, and PSF tables (which can be used for any Chandra ACIS-I data), are available via the public Web site http://astro.imperial.ac.uk/research/aegis/. The AEGIS-X catalog and the optical and IR counterparts catalog are also made available.

We thank the referee for helpful comments that improved the clarity of the paper. We thank those who have built and operate the Chandra X-ray observatory so successfully. We acknowledge financial support from the Leverhulme trust (K.N.), PPARC/STFC (E.S.L., J.A.A.), Marie-Curie fellowship grant MEIF-CT-2005-025108 (A.G.), and Chandra grant GO5-6141A (D.K.K.).

Facilities: CXO (ACIS), CFHT, Spitzer (IRAC).

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