XBOOTES: AN X-RAY SURVEY OF THE NDWFS BOOTES FIELD. I. OVERVIEW AND INITIAL RESULTS

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Received 2004 November 18; accepted 2005 June 23

ABSTRACT

We obtained a 5 ks deep Chandra X-ray Observatory ACIS-I map of the 9.3 deg^2 Bootes field of the NOAO Deep Wide-Field Survey. Here we describe the data acquisition and analysis strategies leading to a catalog of 4642 (3293) point sources with 2 or more (4 or more) counts, corresponding to a limiting flux of roughly 4(8) × 10^-15 ergs cm^-2 s^-1 in the 0.5–7 keV band. These Chandra XBootes data are unique in that they constitute the widest contiguous X-ray field yet observed to such a faint flux limit. Because of the extraordinarily low background of the ACIS, we expect only 14% (0.7%) of the sources to be spurious. We also detected 43 extended sources in this survey. The distribution of the point sources among the 126 pointings (ACIS-I has a 16' × 16' field of view) is consistent with Poisson fluctuations about the mean of 36.8 sources per pointing. While a smoothed image of the point source distribution is clumpy, there is no statistically significant evidence of large-scale filamentary structure. We do find, however, that for θ > 1', the angular correlation function of these sources is consistent with previous measurements, following a power law in angle with slope ~ -0.7. In a 1.4 deg^2 sample of the survey, approximately 87% of the sources with 4 or more counts have an optical counterpart to R ~ 26 mag. As part of a larger program of optical spectroscopy of the NDWFS Bootes area, spectra have been obtained for ~900 of the X-ray sources, most of which are quasars or active galactic nuclei.

Subject headings: galaxies: active — surveys — X-rays: galaxies

1. INTRODUCTION

Many recent extensive multiwavelength surveys of the properties of galaxies and quasars probe only two cosmological regimes—the very local and the very distant. Local surveys (e.g., SDSS, York et al. 2000; or 2dF, Colless et al. 2001) primarily select relatively nearby galaxies and include cosmologically distant active galactic nuclei (AGNs) if they are very luminous. Very deep surveys, like the Hubble Deep Fields, (HDF-N, Williams et al. 1996; HDF-S, Casertano et al. 2000), the GOODS survey (Chatrikristou 2004), or the Chandra Deep Fields (CDF-N, Brandt et al. 2001; CDF-S, Giacconi et al. 2002) cover so little an area (solid angle) that they primarily study distant galaxies and extremely faint AGNs. Medium depth multiwavelength surveys that cover the middle ground and allow us to explore the steady evolution of galaxies and AGNs with cosmic epoch exist (e.g., ChaMP, Green et al. 2004), but none cover the large contiguous areas necessary for detailed studies of clustering and environment.

As a first step toward resolving this problem, the NOAO Deep Wide-Field Survey (NDWFS, Jannuzi & Dey 1999) has obtained deep optical (B, R, I) and near-infrared (K) images of two ~9 deg^2 regions. In this paper we describe our X-ray imaging survey of the Northern (Bootes) field of the NDWFS. In addition to the X-ray data, Bootes has been imaged at radio (VLA FIRST, Becker et al. 1996; WSRT, de Vries et al. 2002), the mid-infrared (Spitzer IRAC, Eisenhardt et al. 2004), the far-infrared (Spitzer MIPS, Soifer et al. 2004), and the ultraviolet (GALEX, Martin et al. 2003). In addition to the imaging survey, the AGN and Galaxy Evolution Survey (AGES, C. Kochanek et al. 2005, in preparation) has obtained redshifts for nearly 10,000 galaxies and quasars selected from the NDWFS optical, X-ray, and infrared photometric samples.

We used the Chandra ACIS-I to survey 9.3 deg^2 of the Bootes field by combining observations carried out as a collaboration of Guest Observer (PI: C. Jones) and Guaranteed Time Observer (PI: S. Murray) programs. A total of 126 contiguous exposures of ~5 ks each were taken, allowing us to reach a limiting sensitivity of ~4 × 10^{-15} ergs cm^-2 s^-1 in the energy range 0.5–7.0 keV. In this paper (Paper I) we outline the data acquisition, reduction and point source detection procedures (§2) leading to the XBootes catalogs denotedXB2 (sources with two or more counts) andXB4 (sources with 4 or more counts). In §3 we discuss the general X-ray properties of the 4642 detected point sources inXB2. The detailed X-ray source catalog will be presented in Paper II (Kenter et al. 2005), which also includes a list of 43 extended sources found in this survey. In particular, in §3.1, we note that the data are consistent with no fluctuations in the source count density on the scale of the ACIS-I field of view (16'). In §3.2 we examine the angular correlation function of the X-ray sources, and in §3.3 we briefly discuss the matches of X-ray sources with NDWFS optical sources. A full discussion of the matches will be given in Paper III (Brand et al. 2005). The results of optical spectroscopy for X-ray-selected sources are discussed briefly in §3.4 and will be the subject of future papers (e.g., C. Kochanek et al. 2005, in preparation). One purpose of this early set of papers (I, II, and III) is to allow us to make

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public the source catalogs in a timely fashion, while providing an adequate reference for the methods used to generate them.

2. X-RAY OBSERVATIONS AND THEIR ANALYSIS

The X-ray observations for this survey were carried out over a 2 week time interval in 2003 March and April, with the individual ACIS-I field centers arranged so that the edges of fields overlapped by about 10'. The Bootes field is centered at R.A. (J2000.0) = 14h32m, decl. (J2000.0) = +35°06'. The spacecraft roll angle was maintained at a constant value for the entire set of 126 5 ks pointings, so that the resulting sky coverage would be as uniform as possible. Figure 1 shows the exposure map for the survey and illustrates the overlap regions, as well as the effects of telescope vignetting. The ACIS-I was operated in Very Faint Mode to allow the best possible background rejection. In Table 1 we provide the observation details and Chandra observation identifiers. These data are all publicly available through the Chandra X-ray Center archive. At total of 630 ks of Chandra observing time was committed to this survey.

In §2.1 we discuss the reduction procedures for the images, and in §2.2 we discuss the source detection procedures. Our procedures are very similar to those used by Kenter & Murray (2003) in their analysis of a smaller survey in the Lockman Hole area. Each ACIS-I field was analyzed independently, and the final source lists are combined.

2.1. Data Preparation

The standard Chandra pipeline products are used with added processing as follows. First, the data are checked for periods of high background or background flares following the CXC data preparation thread. During these observations we had no major background flares, and after screening, most of the individual observations have very much the same exposure time. Almost all of the fields (110 out of 126) have the same exposure time within 100 s, although the full range is from 4250 to 5050 s.

The data are filtered using the very faint mode background (VFM) algorithm developed by Vikhlinin, which also removes afterglow events. Finally, the data are filtered by energy, limiting the energy range to 0.5–7 keV (total band). The final ACIS event files are then binned into image files, with a binning factor of 4 (i.e., 4 × 4 ACIS pixels equal 1 image pixel 1968 on a side). As noted above, these steps are performed on each survey observation individually, resulting in 126 image files used for source detection. In the total band images, the typical background is ~1.1 × 10^-2 counts per image pixel. Of the 126 fields, there are 6 in which the background is about a factor of 2 higher than the rest. However, this higher background has a negligible effect on point source detection efficiency within about 6' of the field center, particularly for sources with ≥4 counts in the detection cell. Figure 2 shows the cumulative sky coverage for the XBootes survey calculated as in Kenter & Murray (2003). Since the exposure times are all very similar, the overall sky

| Chandra ObsID | Type | Date       | Locations |
|--------------|------|------------|-----------|
| 3596–3660    | GTO  | 2003 March | Northern  |
| 4218–4217    | GO   | 2003 April | Southern  |
| 4277–4282    | GO   | 2003 April | Southern  |

7 See http://asc.harvard.edu/cda.

8 See http://asc.harvard.edu/ciao/threads/filter.

9 See http://asc.harvard.edu/cal/Acis/Cal-prods/vfbkgnd.
coverage rises rapidly as a function of flux and exceeds 9 deg$^2$ for a total band flux of $\geq 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$.

2.2. Source Detection

We used the CIAO3.0.2 wavelet detect process (wavdetect) with the sigthresh parameter set to $5 \times 10^{-5}$ to detect point sources in each of the data sets. This relatively high sigthresh parameter value was set on the basis of simulations that showed that for the short exposure times of our survey (and therefore low background) the detection efficiency for faint sources is high and the spurious detection rate is low (see Paper II for details). Because we analyze the fields independently, we may detect the same source twice, if it lies in the overlap region (about 4% of the total area covered). We eliminate these duplications in our source list by selecting the detection that has a smaller radial distance from the aim point (and therefore smaller point-spread function).

The results from running wavdetect (including the elimination of duplicated sources and those with only one count) yields a combined list of 4642 pointlike sources in the 0.5–7 keV energy band that have $\geq 2$ counts within the 90% encircled energy radius. We use this source list as a starting point for further analysis of duplicated sources and those with only one count yields a combined list of 4642 pointlike sources in the 0.5–7 keV energy band. We call this the XB2 catalog. A subset of this catalog with sources of 4 or more counts is denoted as the XB4 catalog and contains 3293 sources.

3. THE DISTRIBUTION OF POINT SOURCES

The source catalog, giving source positions and X-ray properties, is presented in Paper II. We note here that there were 4767 candidate sources from the CIAO wavdetect analysis. From the processing described in the previous section, we find a total of 4642 sources with greater than or equal to 2 counts in the 90% encircled energy region in the 0.5–7 keV total energy band. We call this the XB2 catalog. A subset of this catalog with sources of 4 or more counts is denoted as the XB4 catalog and contains 3293 sources. As a result of simulations, we estimate that the XB2 catalog contains $\sim 14\%$ spurious sources, whereas the XB4 catalog contains less than 1% spurious sources. Here we discuss the spatial distribution of the sources (i.e., their projected sky distribution), along with a brief introduction to the optical matches and subsequent redshift survey.

The 125 candidate sources with fewer than 2 counts within $R_0$, which are not included in XB2, were examined individually and most (114 of 125) were found to have only one event within the 90% encircled energy region appropriate to the off-axis position. Since the wavdetect threshold was set high ($5 \times 10^{-5}$), it is not surprising to have false candidate sources at the level of about 1 per ACIS-I field.

3.1. The Spatial Distribution of Sources

There have been claims in deep surveys covering much smaller areas for the detection of large-scale structure in the distribution of sources (e.g., Yang et al. 2003; Giacconi et al. 2002). In contrast, the ChaMP found source distributions consistent with Poisson statistics in 62 disjoint Chandra fields (Kim et al. 2004). While our survey is not as deep, it is wide, contiguous in area, spatially uniform, performed with a single instrument setup, and contains many more sources that can be divided into spatial regions. Figure 3 shows the spatial distribution of the full set of total band (0.5–7 keV) sources (XB2) on the sky, where each source is represented by a dot (regardless of flux). No obvious significant spatial structure is present.

10 The encircled energy radius (in arcsec) is given by an approximation to the relationship shown in the Chandra Proposer’s Observatory Guide (ACIS-I, for $E = 1.49$ keV), using the functional form $R_{50} = 0.423 + 0.0594 \theta^2$ and $R_{90} = 0.881 + 0.107 \theta^2$, where $\theta$ is the off-axis angle in arcmin.

11 See http://asc.harvard.edu/ca/ASPECT/ceylon.
Figure 4 shows three different approaches to spatially smoothing the distribution of sources. On the left is a “raw image” corresponding to the number of sources in each ACIS-I field (pixels are \( \sim 16\)’ on a side), where the color scale is darkest for the lowest number of sources. The center image is the result of Gaussian smoothing the raw image with a sigma corresponding to one ACIS-I field. There appear to be spatial correlations (i.e., large-scale structures) where the source density is below the average (darker areas that run northeast to southwest) and above the average (brighter areas to the north and west of the dark patches). On the right we show an adaptively smoothed image from Figure 3, where the top-hat smoothing filter has an adaptive size needed to accumulate 38 counts (the average number of sources per ACIS-I field). Structures similar to those seen in the middle panel are also evident in this image. However, the significance of these structures, estimated from the net excess (or deficit) of sources compared with the average over the structure sizes, is only \( 2 \sim 2.5 \sigma \). The structures seen in Figure 4 are typical in appearance and magnitude to structures observed in simulations with random distributions of the same numbers of sources. We can quantify this result by examining the counts-in-cells of the 126 ACIS-I fields of view compared to the Poisson distribution for a mean of 36.84 sources per field (4642/126). As shown in Figure 5 there is no significant difference between the observed and the Poisson distributions. A \( \chi^2 \) test gives a reduced value of 0.90 for 12 degrees of freedom.

While it would be expected that the X-ray–selected AGNs are good tracers of the cosmic web and large-scale structure, it is not very surprising that we find no evidence for large-scale structure based on this technique. Even with \( \sim 4500 \) sources, it would take quite large-amplitude structures to overcome the statistical fluctuations after dividing the data into 126 spatial bins. At \( z \sim 1 \), an ACIS-I field corresponds to about \( 8 \ Mpc \), a scale on which the three-dimensional correlation function should have an amplitude near unity (Croom et al. 2002). In projection, however, we have averaged over the line-of-sight distance, which is 450 times larger than that scale size, and hence we would expect fluctuations of only order \( 1/450^{1/2} \sim 5\% \), which are too small to see against Poisson noise. Clear detections of large-scale structure on these scales will require redshifts (either spectroscopic or photometric), so that the correlations will not be washed out by projection effects along the large line of sight. In § 3.4 we discuss some preliminary results on the redshift distribution of a sample from the XB4 catalog that were obtained from the AGES (C. Kochanek et al. 2005, in preparation), which (when complete) will yield accurate spectroscopic redshifts for about half of the sources in the XB4 catalog as well as some of the optically bright sources at lower flux from the XB2 catalog.

3.2. Large-Scale Structure and Angular Correlation

Statistical evidence of large-scale structure (LSS) in X-ray surveys has been reported by Vikhlinin & Forman (1995), Giaconi et al. (2001), Yang et al. (2003), and others. Previous X-ray surveys looking for LSS typically have been limited to narrow field or disjoint serendipitous surveys with spatially varying levels of sensitivity. The Rontgensatellit survey has further been subject to systematic errors and biases, due to poor angular resolution (Vikhlinin & Forman 1995). These \textit{Chandra} XBootes data are unique in that they constitute the widest (9.3 deg\(^2\)), contiguous...
X-ray field yet observed to such a faint flux limit as $4 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$. The angular resolution, uniform coverage, and large contiguous field of view allow us to search for evidence of structure on both small and large angular scales, relatively free of edge effects and position inaccuracy biases.

In the absence of redshift information, we used the Landy & Szalay (1993) estimator to determine the angular correlation function of the X-ray sources. The random catalogs required for the estimate were generated by drawing sources from the CDS log $N$--log $S$ distribution (Giacconi et al. 2001), and using the MARX (Wise et al. 1997) simulator for the response of Chandra. MARX simulates telescope, detector, and observatory features such as quantum efficiency, inter-CCD chip gaps, vignetting, PSF, and spacecraft dither. We have verified that our Monte Carlo simulations reproduce many features present in the real data, such as the fall-off in detection sensitivity with off-axis angle.

In total, we simulated the entire XBootes field 16 times, detecting 42,000 simulated sources. The simulations reflect all biases and features of the real XB2 data set. Taking into account the integral constraint (Groth & Peebles 1977; Efstathiou et al. 1991), we find a positive angular correlation in the full XB2 source catalog on scales of $\theta > 10$, as shown in Figure 6. The error bars shown are based on Poisson statistics ($\omega = |\omega(\theta) + 1|/DD^{-1/2}$; cf. Wall & Jenkins 2003). The results for $\theta \geq 1'$ are consistent with those previously given by Vikhlinin & Forman (1995), who reported a correlation described by the power law, $\omega(\theta) = (\theta/\theta_0)^{-0.7}$ with $\theta_0 \sim 4''$. On smaller scales, the number of source pairs in our data set is small and we have only upper limits. However, we have plotted the correlation results from Giacconi et al. (2001, their Fig. 6), which extend to small angles and are consistent with our results. Also plotted is the somewhat steeper power law that Giacconi et al. (2001) show in their figure. Our results are fully consistent with these previous correlations.

3.3. Optical Counterparts from the NDWFS

The XBootes X-ray survey field was chosen to cover the same region as the Bootes field of the NDWFS: a deep optical and near-IR imaging survey designed to study the formation and evolution of large-scale structure (Jannuzi & Dey 1999). In this section, we present preliminary results on the identification of the optical ($B_W$, $R$, $I$) and near-IR ($K$) counterparts to the XB4 catalog in a 1.4 deg$^2$ subregion of the full Bootes area. There are 481 X-ray sources in the subregion of which we expect less than 1% to be spurious (Paper II). We find an optical counterpart for 87% of the XB4 X-ray sources. We assign an X-ray source to have an optical counterpart if there is at least one optical source with a detection in at least one optical band in the region enclosed by the X-ray positional errors ($\Delta \theta$; $\sigma_\text{err}$) and $\Delta \theta$.

The NDWFS positions have small astronomical uncertainties (typically 0.01–0.04, rms) that can be considered negligible in comparison to the positional error of the X-ray sources ($\sigma_\text{err}$). Figure 7 shows the cumulative fraction of matches brighter than a given magnitude in the $B_W$, $R$, $I$, and $K$ bands. The $K$-band catalog is not as deep as the optical catalogs and therefore does not match the depth of XBootes, resulting in a smaller fraction of matches. In (Paper III), we present a more sophisticated Bayesian identification scheme that self-consistently evaluates...
the probability of each of the optical sources surrounding an X-ray source being more probable than a “background” source. We also present the matched X-ray/optical catalog for the entire survey area.

3.4. Optical Spectroscopy

The AGES (C. Kochanek et al. 2005, in preparation) targeted all of the XB4 sources matched to an optical source brighter than $R = 21.5$ mag. Fainter X-ray sources from the XB2 catalog were targeted if there were otherwise unallocated fibers. Spectra were obtained with the MMT using the 300 fiber Hectospec robotic spectrograph (Fabricant et al. 1998) in spring and summer of 2004. We (Kochanek et al.) obtained optical spectra for 1231 X-ray–selected targets, and the preliminary reduction of these spectra have resulted in 892 well-determined redshifts and preliminary spectral classifications for these sources. While more work is yet to be done, we find that, as expected, the detection of X-rays preferentially identifies AGNs from the “sea” of galaxies in the NDWFS, and that at the sensitivity level reached in this survey, most of the AGNs are at a redshift of about 1. Of the 892 X-ray objects with preliminary redshifts, 25 are stars, 249 are classified as galaxies, 43 are classified Seyfert 1/2 galaxies, and 575 classified as QSO/Seyfert 1 galaxies. These classifications are based on template matching of the extracted spectra (about 6 Å FWHM resolution) using either a galaxy template (i.e., absorption lines) or an emission line template. The AGNs/Seyfert 1 galaxies have broad lines and the Seyfert 1/2 galaxies have either $[\text{Ne} \text{ v}] 3426$ Å at $>2.5 \sigma$, or $[N \text{ ii}] > H\alpha$, $[O \text{ i}] 6300$ Å exists and $[O \text{ iii}] 5007 \AA > 2 \times H\beta$. It is possible that some of the objects classified as galaxies have lower significance AGN emission lines that were not flagged by this analysis.

The redshift distributions for galaxies (not flagged as any kind of AGN), and AGNs (QSO/Seyfert 1/Seyfert 2) are shown on the left panel of Figure 8. Treister et al. (2004) and Barger et al. (2005) plot redshift distributions for the AGNs found in the Chandra Deep Fields showing peaks near $z = 1$. Barger et al. (2005) give the median redshift as a function of X-ray flux, and for the flux range of the XBootes survey, these are all near $z = 1$. The peak for the XBootes AGN is also peaked around $z = 1$, consistent with these results. With only a preliminary separation of galaxy and AGN classes, it is not appropriate to compare our redshift distribution in detail with those for CDF-S (e.g., Szokoly et al. 2004) or detailed models such as those of Treister et al. (2004). The long tail out to redshifts as high as 3.9 is not surprising, as the survey area is large enough to find rare very high luminosity AGNs at large redshift.
The right panel of Figure 8 shows the distribution of AGNs with a finer binning (0.03 in \(z\)). There are several spikes in the distribution that, if real, would indicate the presence of large-scale structure. We have used a one-sided statistical test of P. Nulsen & S. Murray (2005, in preparation) to search for significant excesses in the redshift bins. Given the sparseness of the data available, we do not consider any of the spikes in our current redshift distribution to be firm evidence for large-scale structure. However, once all of the X-ray–selected AGNs have been observed as part of our ongoing AGES program, there should be about twice the number of objects and therefore sufficient statistics to identify redshift concentrations corresponding to actual large-scale structures.

The quality of the AGES spectra are illustrated in Figure 9, where we show the optical finding chart and preliminary spectrum for one of the highest redshift sources, CXOXB J142547.4+352719 (aka NDWFS J142547.4+352719), a quasar at \(z = 3.53\) that has 12 counts in the total band (0.5–7 keV), corresponding to a luminosity \(L_X = 2.8 \times 10^{45} \text{ ergs cm}^{-2} \text{ s}^{-1}\) (using \(\Lambda\)CDM with \(H_0 = 71, \Omega_m = 0.27, \text{ and } \Omega_{\Lambda} = 0.73\)).

4. CONCLUSIONS

We have conducted a large area survey using 126 Chandra ACIS-I pointings to cover 9.3 deg\(^2\) of the NDWFS in Bootes. We find no evidence for major deviations from a uniform sky.
density of sources at the flux levels reached in ~5000 s of Chandra observing time, but there is some hint of spatial structure on a scale of several Mpc, which may be due to the X-ray–selected AGN population tracing out large-scale structures. The two-point angular correlation for \( \theta \geq 1' \) does show the same power-law correlation as noted previously (e.g., Vikhlinin & Forman 1995; Giacconi et al. 2001).

The X-ray survey and the NDWFS are well matched as evidenced by the high (87%) success rate (Paper III) of associating X-ray sources with optical candidates. Follow-up optical spectroscopy as part of AGES (C. Kochanek et al. 2005, in preparation) has yielded good classification and redshift results, with 892 preliminary redshifts out of 1231 targets, most of which were brighter than \( R = 21.5 \). There are hints in the binned redshift distribution of these X-ray–selected AGNs for excesses at several redshifts. However, the small number of objects per redshift bin does not allow for these to be taken as firm evidence for large-scale structures. These initial redshifts, plus additional spectroscopic redshifts expected from future AGES observations (and ultimately augmented with a comparable number of photometric redshifts) will permit a statistically interesting view of the spatial distribution of the X-ray–selected sources and their relationship to large-scale structures as traced by the galaxy spectroscopy.

This work was supported through the Smithsonian Institution and by NASA contracts NAS8-38248, NAS8-01130, NAS8-39073, and NAS8-03060, and NASA grant GO3-4176A. This work was also supported by the National Optical Astronomy Observatory, which is operated by AURA, Inc., under a cooperative agreement with the National Science Foundation. We appreciate the excellent support we have received from the CXC Mission Planners in carrying out these observations, the CXC Data Processing Team for the pipeline data, the NDWFS Team for the optical observations and data reduction, and the AGES Team in obtaining reduced spectra. We would like to thank the anonymous referee for helpful suggestions that improved this paper.

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