THE CHANDRA LARGE AREA SYNOPTIC X-RAY SURVEY (CLASXS)
OF THE LOCKMAN HOLE–NORTHWEST: THE X-RAY CATALOG

Y. Yang,1,2 R. F. Mushotzky,2 A. T. Steffen,3 A. J. Barger,4,5 and L. L. Cowie5

Received 2004 March 31; accepted 2004 July 8

ABSTRACT

We present the X-ray catalog and basic results from our Chandra Large Area Synoptic X-ray Survey (CLASXS) of the Lockman Hole-Northwest field. Our nine ACIS-I fields cover a contiguous solid angle of ∼0.4 deg² and reach fluxes of 5 × 10⁻¹⁶ ergs cm⁻² s⁻¹ (0.4–2 keV) and 3 × 10⁻¹⁵ ergs cm⁻² s⁻¹ (2–8 keV). Our survey bridges the gap between ultradeep pencil-beam surveys, such as the Chandra Deep Fields (CDFs), and shallower, large-area surveys, allowing a better probe of the X-ray sources that contribute most of the 2–10 keV cosmic X-ray background (CXB). We find a total of 525 X-ray point sources and four extended sources. At ∼10⁻¹⁴ ergs cm⁻² s⁻¹ (2–8 keV), our number counts are significantly higher than those of several noncontiguous, large-area surveys. Such a large difference is an indication of clustering in the X-ray sources. On the other hand, the integrated flux from the CLASXS field, combined with ASCA and Chandra ultradeep surveys, is consistent with results from other large-area surveys, within the variance of the CXB. We see spectral evolution in the hardening of the sources at fluxes below 10⁻¹⁴ ergs cm⁻² s⁻¹, which agrees with previous observations from Chandra and XMM-Newton. About one third of the sources in the CLASXS field have multiple observations, which allow variability tests. Above 4 × 10⁻¹⁴ ergs cm⁻² s⁻¹ (0.4–8 keV), ∼60% of the sources are variable. We also investigated the spectral variability of the variable sources. While most show spectral softening with increasing flux, or no significant spectral change, there are a few sources that show a different trend. We observed four extended sources in CLASXS, which is consistent with the previously measured log N–log S relation for galaxy clusters. Using X-ray spectra and optical colors, we argue that three of the four extended sources are galaxy clusters or galaxy groups. We report the discovery of a gravitational lensing arc associated with one of these sources. Using red-sequence and virial radii, we estimate the inferred masses within the Einstein radii are consistent with the mass profiles of local groups scaled to the same virial radii.

Key words: cosmology: observations — galaxies: active — X-rays: diffuse background

Online material: color figure, machine-readable tables

1. INTRODUCTION

With several ultradeep Chandra and XMM-Newton surveys reaching flux limits as deep as f₂–10 keV ∼10⁻¹⁶ ergs cm⁻² s⁻¹ (Alexander et al. 2003; Giacconi et al. 2002; Hasinger 2004), it is now clear that point sources account for almost all of the X-ray radiation above 2 keV in the universe (Mushotzky et al. 2000; Moretti et al. 2003, hereafter M03). These point sources are believed to be primarily active galactic nuclei (AGNs) on the basis of their X-ray luminosities. It has also been found that only ∼30% of hard-X-ray–selected AGNs show broad lines in the optical, whereas more than 50% appear to be normal galaxies at the sensitivity limits of the current optical spectroscopic follow-up observations (e.g., Barger et al. 2001, 2003). In contrast, the soft-X-ray–selected AGNs from ROSAT surveys are mostly identified as broad-line AGNs in the optical band (Schmidt et al. 1998).

The ultradeep surveys cover very small solid angles. In the case of the Chandra Deep Fields (CDFs), the combined sky coverage is ∼0.2 deg². About 40% variance between fields is seen in the integrated fluxes in the 2–8 keV band (Cowie et al. 2002), likely as a result of the underlying large-scale structure. To determine the fractional contribution of point sources to the cosmic X-ray background (CXB) with enough accuracy and to understand how the CXB sources trace the large-scale structure, a sufficiently large solid angle is needed. While very large area surveys exist above 10⁻¹³ ergs cm⁻² s⁻¹ (2–8 keV) from ASCA (Akiyama et al. 2003), the data around 10⁻¹⁴ ergs cm⁻² s⁻¹, at which the point-source contribution to the CXB peaks, are limited.

Several intermediate, wide-field, serendipitous Chandra/ XMM-Newton surveys (Baldi et al. 2002; Kim et al. 2004; Harrison et al. 2003) were designed to increase the solid angle to several degrees at a 2–8 keV flux limit of 10⁻¹⁴ ergs cm⁻² s⁻¹. One of the advantages of such surveys is that they sample randomly across the sky, so the probability of all of them hitting overdense or underdense regions is small. This is useful in determining the normalization of the log N–log S relation. On the other hand, serendipitous surveys suffer from nonuniform observing conditions for each pointing, and in most cases, the pointings contain bright sources. The biases introduced by these nonuniformities are hard to quantify. The serendipitous surveys also have little power in addressing the question of large-scale structure traced by X-ray–selected AGNs, because
of the small solid angle of each pointing, sparse and random positions on the sky, and the nonuniformity of the observations. With serendipitous surveys, it is also difficult to perform extensive optical spectroscopic follow-up observations, which are critical in obtaining the redshifts and spectral classifications of the X-ray sources. This is due in part to the advent of large-format detectors for imaging and spectroscopy (like those on the Subaru and Keck telescopes), which are more efficient at targeting large-area, contiguous X-ray surveys, rather than many isolated ACIS-I pointings.

A contiguous, large solid angle survey can compensate for these disadvantages and bridge the gap between the ultradeep “pencil-beam” surveys and the large-area serendipitous surveys in determining both the normalization of the log $N$–log $S$ relation and the large-scale structure.

In 2001, we began the Chandra Large Area Synoptic X-ray Survey (CLASXS) of the multiwavelength data-rich Infrared Space Observatory Lockman Hole-Northwest (LHNW) region. The survey currently covers a solid angle of $\sim 0.4$ deg$^2$ and is sensitive to a factor of 2–3 below the “knee” of the 2–8 keV log $N$–log $S$ relation. Such a choice of solid angle and depth maximizes the detection efficiency with Chandra. The large solid angle is important for obtaining statistically significant source counts at the “knee” of the log $N$–log $S$ relation and to test for variance of the number counts on larger solid angles. The choice of solid angle is based on the ASCA results that the rms variance of the 2–10 keV CXB on a scale of 0.5 deg$^2$ is $\sim 6\%$ (Kushino et al. 2002). The expected variance at the angular scale of our field should be less than the uncertainty of the CXB flux. The uniform nature of the survey allows an unbiased measurement of AGN clustering. We have shown that the field-to-field variance seen between the deep fields can be reproduced within the nine fields in our survey (Yang et al. 2003).

Our survey region is covered by the deepest 90 and 170 $\mu$m ISOPHOT observations (Kawara et al. 2004), as well as abundant multiwavelength observations, including the planned Spitzer Space Telescope (SST) Wide-Area Infrared Extragalactic Survey (SWIRE). We performed extensive optical follow-up observations using the Subaru, Canada-France-Hawaii (CFHT), WIYN, and Keck telescopes to obtain multicolor images and spectra of the X-ray sources (Steffen et al. 2004, hereafter S04). These observations provide critical information on the redshifts, spectroscopic classifications, and luminosities of the X-ray sources, as well as on the morphologies of the host galaxies. We emphasize that the subarcsecond spatial resolution of Chandra is critical for the unambiguous identification of optical counterparts.

We describe our observations and data analysis methods in §2 and present our X-ray catalog in §3. In §4, we present the X-ray spectral properties and variability of the point sources. In §5, we present our analysis of the extended sources and report on the discovery of a gravitational lensing arc associated with one of the clusters. We summarize the paper in §6. S04 presents our multiwavelength observations and analysis. We will present the spatial correlation functions of the X-ray sources in a subsequent paper. Throughout this paper, we assume $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$ and a flat universe with $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$.

2. OBSERVATIONS AND DATA REDUCTION

2.1. X-Ray Observations

We surveyed the LHNW field centered at $\alpha = 10^h34^m$, $\delta = 57\degr40'\ (J2000)$. The region has the lowest Galactic ab-

![Fig. 1.—Layout of the nine ACIS-I pointings. The gray-scale map shows the adaptively smoothed full-band image. The exposure maps are added (light gray) to outline the ACIS-I fields. Fields are separated by 10$'$ from each other. The field numbers (LHNW1–9) are shown at the center of each ACIS-I field.](image-url)

sorption ($N_H = 5.72 \times 10^{19}$ cm$^{-2}$; Dickey & Lockman 1990). All nine ACIS-I observations were obtained with the standard configuration. The pointings are separated from each other by 10$'$ (Fig. 1). The fields are labeled LHNW1–9 for reference hereafter. The overlapping of the fields allows a uniform sky coverage, because the sensitivity of the telescope drops significantly at large off-axis angles. Fields LHNW1–3 were observed during 2001 April 30–May 17, and the rest of the fields were observed during 2002 April 29–May 4. All fields except LHNW1 have exposure times of $\sim 40$ ks. LHNW1 is located at the center of the field and has an exposure time of 73 ks. The observations are summarized in Table 1.

We reduced the data with CIAO version 2.3 and the calibration files in CALDB version 2.20. For our spectral analysis, we updated the data reduction with CIAO version 3.01 and CALDB version 2.23 to allow the use of CTI-corrected calibration files. We followed the CIAO analysis threads in reducing the data, including the correction of known aspect problems, CTI problems, and removing high background intervals. Background flares were found in LHNW3 and LHNW6 and have been removed. The resulting event lists were rebinned into 0.4–2 keV (soft), 2–8 keV (hard), and 0.4–8 keV (full) broadband images. Spectrally weighted exposure maps were made for each band for each observation using the observation-specified bad pixel files.

2.2. Source Detection

The detection sensitivity of Chandra drops rapidly beyond 6$'$ off-axis. For this reason, we overlapped our ACIS-I fields so that the sensitivity of the survey would be uniform across the field. Since the added signal-to-noise ratio from merging the

⁶ Available online at http://asc.harvard.edu/ciao.
observations is relatively small, we chose to detect sources in each observation individually and merge the catalogs rather than to detect sources directly on the merged image. This method certainly loses some sensitivity for very dim sources at some locations. However, since our major interest is to obtain a uniform sample for statistical and follow-up purposes, such a choice is justified. The method also simplifies the source flux extraction because the point-spread function (PSF) information could easily be used. Multiple detections of sources in independent observations are very useful for checking and improving the X-ray positions of the sources. Multiple detections also provide an opportunity for measuring the variability of these sources.

From the various detection tools available, we chose to use the \texttt{wavdetect} tool included in the CIAO package (Freeman et al. 2002). Since \texttt{wavdetect} uses a set of scales to optimize the source detection, the tool is excellent at separating nearby sources in crowded fields. In general, the method also provides better sensitivity than the classical “sliding-box” methods. The drawbacks of \texttt{wavdetect} are that it runs rather slowly on large images like the full-resolution ACIS-I images and that it requires fine tuning of the parameters.

We ran \texttt{wavdetect} on the full-resolution images with wavelet scales of $1, \sqrt{2}, 2, 2\sqrt{2}, 4, 4\sqrt{2}$, and 8. Although using larger scale sizes could help to detect very far off-axis sources, it is not very useful for our survey because of the overlapping of fields. It also increases the computation time to use a large number of scales. We chose to use a significance threshold of $10^{-7}$, which translates to a probability of false detection of 0.4 per ACIS-I field based on Monte Carlo simulation results (Freeman et al. 2002).

2.3. Source Positions

Observations performed before 2002 May 2 suffer from an systematic aspect offset as large as 2" from an error in the pipeline software. This systematic error was carefully calibrated by the \textit{Chandra} X-ray Center, and corrections are provided. For the affected fields, LHNW1, 2, 3, 4, 5, and 7, we corrected this error following the standard procedures. 

We further matched the small off-axis X-ray positions reported in each field from \texttt{wavdetect} to the optical images. Corrections were then found that maximized the matches. Such corrections are very small. The astrometric improvement also only marginally improved the matching between the X-ray catalogs, thanks to the excellent astrometric accuracy of the instrument. The corrected X-ray catalogs from each observation were then merged (§3.1). A further absolute astrometric correction was applied to the merged X-ray catalog to match to the radio sources in the field. In Figure 2, we show the offsets between the corrected positions and the optical positions for sources in different off-axis angle ranges. Large offsets often occur when the X-ray source is at large off-axis angles. Offsets are generally small, with a dispersion of 0'23 for all the sources detected.

2.4. Source Fluxes

The \texttt{wavdetect} program is excellent at detecting sources, but it is not always the best method for flux extraction. Three issues could contribute to an incorrect estimation of source counts in \texttt{wavdetect}. First, the flux measurements in \texttt{wavdetect} use a monochromatic PSF size, which, by default, corresponds to an enclosed energy of 0.393 at the energy of choice, or the 1 $\sigma$ integrated volume of a normalized two-dimensional Gaussian. Although this parameter is adjustable, larger enclosed energy

![Fig. 2.—Offset between the corrected X-ray positions and the optical positions. The 135’ and 45’, as measured from the positive x-axis, shaded histograms show the offsets within 4’ and between 4’ and 6’ of the optical axis, respectively. The unshaded histogram shows the sources with off-axis angles greater than 6’.

\begin{table}[h]
\centering
\caption{Observation Summary}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Target Name & $\alpha_{2000}$ & $\delta_{2000}$ & Observation ID & Sequence & Observation Date \tabularnewline
\hline
LHNW1 & 10 34 00.24 & +57 46 10.6 & 1698 & 900057 & 2001 May 17 18:29:38 \tabularnewline
LHNW2 & 10 33 19.82 & +57 37 13.8 & 1699 & 900058 & 2001 Apr 30 10:59:38 \tabularnewline
LHNW3 & 10 34 36.12 & +57 37 10.9 & 1697 & 900056 & 2001 May 16 12:46:50 \tabularnewline
LHNW4 & 10 32 04.20 & +57 37 15.6 & 3345 & 900184 & 2002 Apr 29 03:23:45 \tabularnewline
LHNW5 & 10 34 00.31 & +57 28 15.6 & 3346 & 900185 & 2002 Apr 30 02:03:59 \tabularnewline
LHNW6 & 10 33 20.28 & +57 55 15.2 & 3343 & 900182 & 2002 May 3 09:11:41 \tabularnewline
LHNW7 & 10 32 44.23 & +57 46 15.2 & 3344 & 900183 & 2002 May 1 20:03:06 \tabularnewline
LHNW8 & 10 34 36.26 & +57 55 15.6 & 3347 & 900186 & 2002 May 2 14:16:27 \tabularnewline
LHNW9 & 10 35 14.28 & +57 46 15.2 & 3348 & 900187 & 2002 May 4 11:01:47 \tabularnewline
\hline
\end{tabular}
\footnotesize{Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. 
$^a$ Total good time with dead-time correction.}
\end{table}
values could cause confusion of close sources. Since the construction of source cells is carried out by convolving the source image with wavelet functions, the “smearing” effects of the convolution can in general make the source cell large enough to include most of the source photons, but the fraction of the flux recovered varies from source to source. Second, because of the statistical fluctuations in the source photon distribution, some sources show multiple peaks in the convolved image. Unless perfect PSF information is available, randomness should exist in determining which of the peaks belong to a single source. This problem is particularly severe when the source is very off-axis and the PSF shape cannot be approximated by a Gaussian. The third issue is the background determination, a problem other methods also share. The background in wavdetect is obtained in the immediate neighborhood of the source. This is useful because of the known large background fluctuations. However, if the background is drawn too close to the source, the PSF wing would likely be taken as background. This could result in an oversubtraction of the background and lead to underestimated source counts. This effect is seen in a correlation of source counts with background density in the wavdetect results. All of these issues would lead to an underestimation of source counts. This has been noticed in the analysis of the deep Chandra fields (Giacconi et al. 2002; A. Hornschemeier 2003, private communication).

Because of the spectral differences of the sources and the sensitivity differences between energy bands, sources detected in one band are not always detected in another at high significance. There is no simple way within wavdetect to provide upper limits for these sources. To obtain the source fluxes or upper limits in the nondetection band, an alternative flux extraction method is needed.

For these reasons, we wrote an aperture photometry tool for source flux extraction. The method uses a simple circular aperture that matches the size of the PSF. To do this, we first compared the broadband PSFs derived from our observations with the PSF size file provided with CIAO, as described below.

### 2.4.1. Broadband PSFs

Both the PSF library used by the CIAO tool mkpsf and the circularly averaged PSFs used by the detection codes (psfsize20010416.fits) are generated at monochromatic energies using simulations of the telescope. The spectrally weighted average energy is usually used for selecting the PSF file for broadband images. Since the spectra of the X-ray sources are mostly unknown, an average spectrum has to be assumed. Whether such selected PSFs agree with the observed broadband PSFs needs to be tested. We constructed “average PSFs” for different off-axis angles using sources that have no neighbors within 40" in our nine observations (Fig. 3). It should be noted that these PSFs are inaccurate at large scales because the PSF wings, which span more than 1", could not be well determined in these observations. The source images from the same off-axis annuli are stacked, and the curves of growth are constructed. The background regions are fitted with quadratic forms using nonlinear least-square fits. To compare with the library PSFs used by wavdetect, we linearly interpolated the library PSFs to the off-axis angles and the spectrally weighted averaged energies. To account for the fact that part of the PSF wings had been fitted as background in our data, we did the same “background fitting” on the interpolated PSFs. This allows a comparison of the observed curve with the interpolated PSF. The broadband PSFs are generally narrower than the interpolated PSFs, except for one case in the hard band for which the off-axis angle is large.

### 2.4.2. Aperture Photometry

We performed our flux extractions in the following way. We used circular extraction cells, choosing the radius of cells from the PSF library at a nominal enclosed energy of ~95% (the true enclosed energy should be greater than 95% based on the discussion above) if the cell size is greater than 2". For sources close to the aim point, a fixed 2.5" radius was used. The background is estimated in an annulus region with an area 4 times as big as the source cell area, with an inner radius 5" larger than the source cell radius. To avoid nearby sources being included in the background region, the background region is divided into eight equal-sized segments (Fig. 4). The mean background counts are estimated, excluding the segment that contains the highest number of events. Then the 3σ
Poisson upper limit is derived using the approximations provided in Gehrels (1986). The background is then recalculated with only the background segments that contain counts less than the upper limit. The net counts are obtained by subtracting the background from the source counts within the source cell. We compare the obtained net counts with the net counts obtained with \textit{wavedet} (Fig. 5). Although they mostly agree, the source photons derived from our method are, on average, higher than those from \textit{wavedet}, especially for low-count sources. The average increases are 4%, 7%, and 8% for the soft, full, and hard bands, respectively. We hand-checked the sources with large discrepancies from the two methods, and we found our estimates to be more reliable.

2.4.3. Exposure Time and Flux Conversion

The prerequisite for using exposure maps is that the effective area is only weakly dependent on energy. This is not the case for our broadband images, in which the effective area changes rapidly with energy. Using exposure maps blindly, even the spectrally weighted ones, will inevitably introduce large errors in the resulting fluxes. However, the vignetting (the positional changes of sensitivity) is less sensitive to energy. In other words, if we normalize the exposure maps obtained at different energies to the aim points, then the differences between such “normalized exposure maps” are very small.

Based on this fact, we use the exposure maps only to correct for vignetting and compute the flux conversion at the aim point using spectral modeling. We first make full-resolution spectrally weighted exposure maps. (Using monochromatic maps do not change the results significantly.) For each source, the exposure map is convolved with the PSF generated using \textit{mkpsf} and normalized to the exposure time at the aim point. This is the effective exposure time if the source is at the aim point.

The conversion factor is then obtained at the aim point by assuming the source has a galactic, absorbed, single–power-law spectrum. The power-law index is calculated using the hardness ratio of each source, defined as \( HR \equiv C_{\text{hard}} / C_{\text{soft}} \), where \( C_{\text{hard}} \) and \( C_{\text{soft}} \) are the count rates in the hard and soft bands, respectively. XSPEC was used in computing the conversion from \( HR \) to \( F \) and for calculating the conversions. The degradation of quantum efficiency during the flight of the observatory has been accounted for using the standard procedure.

3. CATALOG

3.1. Merging Catalogs

We first merged the three band catalogs. We used a 3 \( \sigma \) error ellipse from the \textit{wavedet} output as the identification cell. Flux extraction was then performed on all entries in the merged catalogs in all bands using the best position of the sources. We compared the three band catalogs with the optical catalog to find the astrometric corrections for each observation, as described in § 2.3. The nine catalogs were then merged. The fluxes of the sources with more than one detection in the nine fields were taken from the observation in which the effective area of the source was the largest, except for those sources with more than two detections having normalized areas greater than 80%, for which we took the averaged flux. We visually checked the final catalog to ensure the correctness of the merging process. The final catalog contains 525 sources.

The distribution of the source off-axis angles in the merged catalog is shown in Figure 6. It can be seen that most of the sources fall within a range of less than 6’. Figure 7 shows the distribution of sources with multiple detections. About one third of the sources have more than one observation.

3.2. Column-by-Column Description of the Catalog

We present the final catalog in two tables (Tables 2 and 3). In Table 2, we list the source positions, fluxes, and hardness ratios. In Table 3, we list the source net counts, effective exposures, and detection information. The columns of Table 2 are as follows.

![Fig. 4](attachment:image.png)

**Fig. 4.—** Examples of the source and background regions used in the flux extraction. The smaller circle is the source region. The background regions are shown as segments of an annulus. Segments with counts below 3 \( \sigma \) of the mean are used in the final background estimation and are marked with crosses. (a) An isolated source; (b) a source with a close neighbor.
Fig. 5.—Comparison of net counts from \textit{wavdetect} and our aperture photometry (marked as XPHOTO) for the (a) soft, (b) hard, and (c) full bands.

Fig. 6.—Distribution of off-axis angles of the best positions.

Fig. 7.—Distribution of multiple detections.
bands, respectively, in units of 10⁻⁸/C₀ and the nine observations, the best position is taken.

2.3). For sources with multiple detections in the three bands x astrometric solution by comparing with the optical images (see "5.2").

For any source detected in one band but with a very weak signal in another, the background-subtracted flux could be detected in multiple observations and if there is more than 80% of the effective area at the aim point, then the mean flux is used; otherwise, the flux from the observation that has the largest effective area is used. As in Table 2, for the sources with negative counts, only the upper limits are listed.

If a source is detected in multiple observations and if there is more than 80% of the effective area at the aim point, then the mean flux is used; otherwise, the flux from the observation that has the largest effective area is used. Column (9) lists the LHNW field numbers (each digit represents a field number) in which the source has been detected in at least one of the three bands. Sources with multiple detections are necessary for the detection of variability (see § 5.2).

4. RESULTS

4.1. Number Counts

4.1.1. Incompleteness and Eddington Bias

Incompleteness can be caused by energy or positional dependence of the sensitivity of X-ray telescopes. Because the spectrum of a source carries important information on the physical nature of the source itself, sources of different spectra are usually categorized as different types. The energy-dependent sensitivity acts like a filter in selecting “hard” and “soft” types of X-ray sources. The soft band–detected sources always contain more soft-spectrum objects than the hard band–detected sources and vice versa. Unless the fraction of each type remains constant for all fluxes (which we now know is not true), the energy-dependent incompleteness cannot be easily corrected. This issue is very important in interpreting the fraction of different types of objects in flux-limited surveys. It is desirable to obtain number counts for each type of source, but it is hard to do that for the CXB sources, because the spectra are hard to determine. For our medium-deep survey, it is sensible to follow tradition and only discuss the number counts in energy bands.

The positional-dependent incompleteness is caused by vignetting and aberration of the X-ray optics. The vignetting causes the effective area to drop off-axis angle, and the aberration makes the off-axis PSF larger so that it includes a larger number of background events in the source cell. The net effect is that

Columns (8)–(9).—Detection information. Column (8) is the LHNW field number for which the source has the largest effective area. Column (9) lists the LHNW field numbers (each digit represents a field number) in which the source has been detected in at least one of the three bands. Sources with multiple detections are necessary for the detection of variability (see § 5.2).

4. RESULTS

4.1. Number Counts

4.1.1. Incompleteness and Eddington Bias

Incompleteness can be caused by energy or positional dependence of the sensitivity of X-ray telescopes. Because the spectrum of a source carries important information on the physical nature of the source itself, sources of different spectra are usually categorized as different types. The energy-dependent sensitivity acts like a filter in selecting “hard” and “soft” types of X-ray sources. The soft band–detected sources always contain more soft-spectrum objects than the hard band–detected sources and vice versa. Unless the fraction of each type remains constant for all fluxes (which we now know is not true), the energy-dependent incompleteness cannot be easily corrected. This issue is very important in interpreting the fraction of different types of objects in flux-limited surveys. It is desirable to obtain number counts for each type of source, but it is hard to do that for the CXB sources, because the spectra are hard to determine. For our medium-deep survey, it is sensible to follow tradition and only discuss the number counts in energy bands.

The positional-dependent incompleteness is caused by vignetting and aberration of the X-ray optics. The vignetting causes the effective area to drop off-axis angle, and the aberration makes the off-axis PSF larger so that it includes a larger number of background events in the source cell. The net effect is that

Columns (8)–(9).—Detection information. Column (8) is the LHNW field number for which the source has the largest effective area. Column (9) lists the LHNW field numbers (each digit represents a field number) in which the source has been detected in at least one of the three bands. Sources with multiple detections are necessary for the detection of variability (see § 5.2).
the sensitivity of source detection drops with increasing off-axis angle. The sky area is therefore flux-dependent.

These effects can be investigated via Monte Carlo simulations. We first generated background images using observations of fields 1 and 4, which represent the 70 and 40 ks exposures, respectively. Point sources are removed from the images, and the holes left in the images are filled by sampling the local background images. Random sources are generated uniformly on the background images. The fluxes of the sources are generated by randomly sampling a complete subset of the combined Chandra Deep Fields catalog (Alexander et al. 2003). The subset contains only sources with hard-band fluxes greater than \(5 \times 10^{-16} \text{ ergs cm}^{-2} \text{s}^{-1}\) and effective exposure times greater than 200 ks. The input fluxes are converted to on-axis counts, assuming power-law spectra with \(\Gamma = 1.4\). The exposure map for each image is consulted to find the vignetting effect at the source location, and the normalized exposure is multiplied by the true counts to obtain the “observed” net counts. Only sources with more than 3 counts are used in the simulation to avoid adding too many undetectable dim sources to the background. We use the CIAO tool mkpsf to generate realistic source shapes at the source positions and energies. The PSF is then sampled to have the same number of photons as in the source. We chose to use mkpsf instead of using the Chandra simulator MARX because we find that the PSF library used by mkpsf better resembles sources at large off-axis angles. The number density of the sources is chosen to be 2 times higher than the observed density to increase the number of simulated sources without affecting detections. We ran 100 simulations on the two fields and the three energy bands and detected the sources using wavdetect with identical parameter settings to those we used in preparing the observed catalog. Because of the large computation time, the number of simulations that can be done is limited.

We then compared the output catalogs with the input source catalogs. Because of the small size of the simulation, the completeness within 4′ is not well determined, and a 5% uncertainty exists in the determined fractions. Fortunately, the PSF effect is small at such small off-axis angles. For a given flux threshold, the fraction of source detections drops monotonically with off-axis angle. This relation is fitted between 4′ and 10′ with a linear least-squares fit. The 95% complete off-axis angle limit is then taken from the interpolation of the fit. The resulting flux thresholds versus off-axis radii are shown for the three bands and the two exposure times in Figure 8. We note that at large off-axis angles, the sensitivity drops rapidly. This is due to the choice of wavelet scales. When the largest scale used becomes smaller than the PSF size of the source, wavdetect is no longer sensitive. This effect, however, is not important for our observations, because most of the sources of interest are within 6′ off-axis, thanks to the overlapping of fields. With these curves, we are able to make threshold maps for the combined catalogs of all three bands. Sources at very large off-axis angles are excluded from the study of the log \(N\)–log \(S\) relation. The combined solid angle versus flux thresholds are shown in Figure 9.

The Poisson fluctuations in the source fluxes could result in an overestimation of number counts close to the detection limits. This is known as the Eddington bias. The effect depends both on the slope of the log \(N\)–log \(S\) relation and the level of fluctuation. For the CLASXS field, the detection threshold is below the “knee” of the log \(N\)–log \(S\) relation, and the Eddington bias is relatively small. We corrected this bias using the method described in Vikhlinin et al. (1995). In

![Figure 8](image_url)

**Figure 8.**—Thresholds for 95% completeness vs. off-axis angle. Sources with flux and off-axis angle combinations above these curves are complete. Solid, dashed, and dotted lines represent the threshold curves for the soft, hard, and full bands, respectively. Squares represent the 70 ks exposure, and diamonds represent the 40 ks exposure.

For the soft band, the correction is only important below \(2 \times 10^{-15} \text{ ergs cm}^{-2} \text{s}^{-1}\). For the hard band, the correction is important below \(8 \times 10^{-15} \text{ ergs cm}^{-2} \text{s}^{-1}\). We fit flux-threshold curves in Figure 10 for the different off-axis angles with fourth-order polynomials and correct the source fluxes in the observed catalog using these fits.

4.1.2. The Number Counts

Sources are selected by consulting the threshold map at the source positions and including only those with Eddington bias–corrected fluxes higher than the threshold map values. Sources very far off-axis are excluded from the analysis. With these selections, we used a total of 310 and 235 sources in the soft and hard bands, respectively, to construct the log \(N\)–log \(S\) relations. The cumulative log \(N\)–log \(S\) relations are computed using the formula

\[
N(>S) = \frac{1}{2\Omega(S_i)} \frac{1}{\Delta S},
\]

where \(\Omega\) is the complete solid angle. We show the results in Figure 11 in the soft and hard bands with 1 σ Poisson errors. The differential log \(N\)–log \(S\) relations for the two bands are shown in Figure 12 and are calculated using the formula

\[
\frac{dN}{dS} = \frac{1}{\Omega(S) \Delta S}.
\]

in units of \(\text{deg}^{-2}\) per \(10^{-15} \text{ ergs cm}^{-2} \text{s}^{-1}\). We fit the resulting differential number counts with single or broken power laws of the form

\[
\frac{dN}{dS} = n_0 \left( \frac{S}{10^{-14}} \right)^{-\alpha}
\]

using error-weighted least-square fits. Since our survey best samples the “knee” of the log \(N\)–log \(S\) relation, the slope of
Fig. 9.—Survey effective solid angle vs. flux. Soft band (solid line); full band (dashed line); and hard band (dotted line).

Fig. 10.—Average output fluxes from \texttt{waredetect} vs. average input fluxes for the simulated sources at a set of off-axis angles (diamonds). The Eddington bias is seen in the overestimates of output flux at low fluxes. The bias also increases at large off-axis angles. The best fit of the biases are shown as dotted lines for off-axis angle intervals 0°–2.5°, 2.5°–4°, 4°–6°, 6°–8°, and greater than 8°.

Fig. 11.—Cumulative log $N$–log$S$ relations for the soft and hard bands. The 1 σ error is shaded. The dash-dotted line represents the best fit from M03. The hard-band log $N$–log$S$ relation from M03 is rescaled to that of 2–8 keV, assuming $\Gamma = 1.4$. 
the power laws are not well constrained because of the lack of data points both far above and below the “knee.” On the other hand, $n_0$ is better determined, to within 1%.

For the soft band, we fit the number counts between $10^{-15}$ and $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ with a power law. We find the best-fit parameters to be $\alpha = 1.7 \pm 0.2$ and $n_0 = 12.49 \pm 0.02$. The slope is in good agreement with previous observations, such as the Chandra Deep Field-North ($1.6 \pm 0.1$; Brandt et al. 2001), SSA13 ($1.7 \pm 0.2$; Mushotzky et al. 2000), and the compiled wide fields from Chandra, XMM-Newton, ROSAT, and ASCA ($1.60^{+0.02}_{-0.01}$; M03). The normalization also shows excellent agreement with the compiled results from the large-area survey of M03, which has an effective solid angle at $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ larger than that of CLASXS. Above $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, the slope steepens, but the fluctuations in the number counts make it difficult to find a reasonable fit. However, the log $N$–log $S$ relation is apparently consistent with a slope of $\alpha = 2.5$, shown as the dotted line at these fluxes.

Similarly, we model the hard-band number counts with a broken power law and obtain the following best-fit parameters. For $S > 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, $\alpha = 2.4 \pm 0.6$ and $n_0 = 45.6 \pm 0.5$; for $3 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1} < S < 2 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, $\alpha = 1.65 \pm 0.4$ and $n_0 = 38.1 \pm 0.2$. For comparison, we also plot the best-fit cumulative log $N$–log $S$ relation from M03 and the differential log $N$–log $S$ relations from the SEXSI fields (Harrigan et al. 2003) and from Cowie et al. (2002). At fluxes below $8 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$, the differential log $N$–log $S$ relation for all the fields agrees within the errors. The difference in the total counts at a flux limit between the CLASXS field and the M03 fields is also small. An apparent difference is seen around $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$: the total counts at $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ are 70% higher than those from M03. This is significant at greater than the 3 $\sigma$ level.

The integrated flux between $3 \times 10^{-15}$ and $8 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ from the log $N$–log $S$ relation is $(1.2 \pm 0.1) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ deg$^{-2}$. This is 20% higher than that from M03 and SEXSI in the same flux range. Since there is little difference in the number counts between the CLASXS fields and the other large solid angle surveys at fluxes lower than $8 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$, we should expect little difference below the survey limit on the same angular scales. If integrated to lower fluxes and including the integration from ASCA above $8 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, the fractional difference between the CLASXS field and the other large solid angle surveys can be reduced to 10% without considering the possible biases. This difference is higher than expected from the variance in the CXB from ASCA observations but is consistent with recent observations with the RXTE PCA, in which a 7% variance is seen among several $\sim 1$ deg$^2$ fields (Revnivtsev et al. 2003). The uncertainty of the hard CXB itself is $\sim 10% - 15%$. The differences in the integrated point-source fluxes from various large fields are within this uncertainty. In terms of the true contribution from point sources to the CXB, a field with a solid angle of $\sim 0.3$ deg$^2$ seems to be large enough to be representative.

The detection of the large variance in the hard-band source counts around $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ on our survey scale seems to indicate that the sources that emerge at this flux are more clustered on the sky than the soft band–selected sources. These sources could account for most of the cosmic variance observed. This issue will be discussed in a separate paper.

4.2. Spectral Properties and Variability of the CXB Sources

4.2.1. Hardness Ratio

We employ a hardness ratio (§ 2.4.3) to statistically quantify the spectra of the CXB sources in our field. Figure 13 shows the distribution of hardness ratio versus full-band flux. We have also marked the hypothetical photon indices ($\Gamma$), assuming the hardness ratio change is purely due to the slope change of a single power-law spectrum. At fluxes greater than $3 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, most sources cluster around $\Gamma \sim 1.7$. At lower fluxes, the hardness ratio distribution scatter increases, and the relative number of hard sources increases. Below $3 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$, the data show a paucity of hard sources. This is a selection effect caused by the sensitivity in the hard band being lower than in the soft band for most spectra. We stacked the sources in flux bins and calculated the hardness ratios of the stacked spectra. Figure 14 shows the stacked hardness ratios from both the CLASXS greater than $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ sample and the combined CDFs greater than $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ sample. The flux thresholds are chosen to avoid selection effects caused by the sensitivity differences between the soft and hard bands. It is apparent that the results from our data and those from the CDFs agree well.

The spectral flattening at low fluxes has been observed by several authors (e.g., Mushotzky et al. 2000; Tozzi et al. 2001; Piconcelli et al. 2003; Alexander et al. 2003) with observations of different depths. Spectral analyses with XMM-Newton observations indicate that such a flattening is mainly caused by absorption. These obscured AGNs must dominate the population around the “knee” of the log $N$–log $S$ relation to account for the flat spectrum of the CXB. Since most of the XMM-Newton spectral observations have reached a few times $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ (Piconcelli et al. 2002) and the mean spectrum at this threshold is still too soft compared with that of the CXB, a sharp increase of obscuration or a change of spectral shape at a flux of $\sim 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ is inevitable. Such a sharp change is seen in the change of hardness ratio in our wide-field sample.

4.2.2. Variability

X-ray variability is an important factor in distinguishing AGNs from starburst galaxies. Almost all AGNs vary in X-rays, except those that are Compton thick. Alexander et al.
Fig. 13.—Hardness ratio vs. full-band flux for the CLASXS sources. Open circles with arrows represent the upper or lower limits. Dashed lines with numbers label the hypothetical spectral indices, assuming the source spectra are single power laws with only Galactic absorption. The dotted line represents the typical error size of the hardness ratio for a source with hardness ratio of 1.

Fig. 14.—Hardness ratio of the stacked sources in different flux bins. Crosses are the CLASXS sources, and diamonds are the combined CDFs sources (Alexander et al. 2003). Sources with fluxes below $8 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ in the CLASXS catalog and $1 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ in the CDFs catalogs are not included to avoid incompleteness. Dashed lines are as in Fig. 13.
Fig. 15.—Light curves of the sources detected to be variable. The fluxes are normalized to the mean of all the observations. Numbers in the plots are the source numbers in the catalog. (a) Soft band; (b) hard band; and (c) full band.
(2001) showed that only a small fraction of the optically faint X-ray sources vary. Possible explanations could be that a large fraction of the optically faint sources are Compton thick or that the amplitude of variation of the optically faint sources is much lower than that of the broad- and/or narrow-line AGNs at the same flux thresholds.

We examine the variability of sources that have been detected in more than one of our observations. Since the observations were taken in two groups, separated by \( \sim 1 \) yr, and each group of observations were taken within a few days (see Table 1), we are able to test variability on timescales of days and/or 1 yr, depending on the location of the source.

For timing analyses with low counts per bin, the usual \( \chi^2 \) statistic is inadequate. We use the \( C \)-statistic (Cash 1979) in testing the significance of variability. Cash (1979) showed that the \( C \)-statistic (a reduced form of the likelihood ratio) written as

\[
\Delta C = -2 \sum_{i=1}^{N} [n_i \ln(e_i) - e_i - n_i \ln(n_i) + n_i]
\]

is asymptotic to a \( \chi^2 \) distribution with \( N - 1 \) degrees of freedom, where \( n_i \) is the observed counts in the \( i \)th sample, \( e_i \) is the expected counts in that sample, and \( N \) is the total number of samples used. We restricted the sample for the variability test to sources with expected counts greater than 10 in all observations. The null hypothesis rejection probability was chosen to be 0.01.

A total of 168 sources were tested for variability, of which 42 sources are significantly variable and 28 sources show variability on timescales of days. There are 29, 16, and 30 variable sources detected in the soft, hard, and full bands, respectively.

Figure 15 shows the light curves of the sources that were tested to be variable in any of the three energy bands. In the top panel of Figure 16, we show the fraction of variable sources detected versus flux. Between 4 and \( 8 \times 10^{-14} \) ergs cm\(^{-2}\) s\(^{-1}\), 70% of the sources tested show variability. This fraction drops dramatically as the flux decreases and at \( 10^{-14} \) ergs cm\(^{-2}\) s\(^{-1}\) reaches below 20%. This is at least in part due to the selection effect that larger variability is needed at lower fluxes to make the test significant. At fluxes above \( 8 \times 10^{-14} \) ergs cm\(^{-2}\) s\(^{-1}\), only one of the four sources tested (25%) was found to be variable.
Following Nandra et al. (1997), we define the magnitude of variability as the “excess variance,” the error-subtracted rms variance

$$\sigma_{\text{rms}}^2 = \frac{1}{N\mu^2} \sum_{i=1}^{N} \left[ (f_i - \mu)^2 - \sigma_i^2 \right],$$  \hspace{1cm} (5)

where $f_i$ is the flux in each observation, $\mu$ is the mean of the fluxes, and $\sigma_i$ is the Poisson error of the flux. By assuming the same power density spectrum of X-ray variability for all AGNs, $\sigma_{\text{rms}}^2$ can be used as a good indicator of whether the variability exceeds the Poisson noise. It has been found that there exists a good anticorrelation between $\sigma_{\text{rms}}^2$ and AGN luminosity (Nandra et al. 1997) in local AGN samples.

In Figure 17, we show the excess variance of sources that had been detected to be variable versus X-ray flux in the three energy bands. At high fluxes, the average $\sigma_{\text{rms}}^2$ is significantly lower than at lower fluxes. As mentioned above, variability is harder to detect for low-flux sources, unless the source is more variable than that of the brighter sources, so this bias could explain why there are very few low-flux, low-variability sources in the plot. In addition, the sources we detect to be variable are generally soft. This is consistent with the observation from the CDFs that optically faint sources (most of which are hard-spectrum AGNs) are less variable (Alexander et al. 2001).

4.2.3. Spectral Variability

Very little is known about the spectral variability of the sources that contribute the most to the CXB because of a lack of data. Spectral variability is seen in about half of the well-studied brighter sources, with a general trend of softening of the 2–10 keV spectra with increasing source intensity. However, a counterexample is NGC 7469, in which the spectrum flattens when the source flux increases (Barr 1986). The variability could be accounted for either with a change in the relative normalization of the different spectral components or by variation in the absorption.

In Figure 18, we show hardness ratios versus full-band fluxes for the variable sources. Although most of the sources show either no clear spectral variability or a trend of spectral softening with increasing flux, there are a number of sources that clearly become harder with increasing flux. There are also a few sources that exhibit a mixed trend. On average, these sources tend to have softer spectra with increasing flux.

5. EXTENDED SOURCES

5.1. Detection

We searched the 0.4–2 keV images of each observation for extended sources using the vipdetect tool provided in CIAO. The method uses Voronoi tessellation and percolation to identify dense regions above the Poisson noise. This method performs best on smooth overdense regions but could confuse crowded point sources. We chose to use a threshold scale factor of 0.8 and a maximum probability of false detection of $10^{-6}$ and to restrict the number of events per source to more than 30. We used default values for the rest of the parameters. This choice of parameters maximizes the detection of low surface brightness sources of high significance. We visually examined the source list to screen out apparent blended point sources. The candidates were then selected by comparing the 99% PSF radius with the equivalent radius of the source region, and only sources with a PSF ratio [defined as $(A/\pi)^{1/2}/r_{99}$, where $A$ is the area of the source region reported by vipdetect and $r_{99}$ is the 99% PSF radius at the off-axis angle] higher than 10 were considered extended (Table 4).

Four sources were found to be significantly extended, and all but source 3 have an off-axis angle of less than 5° in the X-ray observations. Source 3 is at an off-axis angle of 8°4. With the X-ray image alone, one could not rule out the source.
Fig. 18a

Fig. 18.—Spectral variability vs. full-band fluxes for all the variable sources. The fluxes are in units of $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$. Numbers on top of each plot are the source numbers in the catalog.
TABLE 4  
**EXTENDED SOURCES**

| Source Number | $\alpha_{2000}$ | $\delta_{2000}$ | $\Delta\alpha$ (arcsec) | $\Delta\delta$ (arcsec) | $\theta^a$ (arcmin) | PSF Ratio$^b$ | Net Counts$^c$ | Field$^d$ |
|---------------|------------------|------------------|------------------------|-----------------------|-------------------|--------------|-------------|---------|
| 1.................. | 10 35 25.4 | +57 50 48 | 2.628 | 1.044 | 4.786 | 37.89 | 100.1 ± 11 | 9 |
| 2.................. | 10 35 13.4 | +57 50 17 | 3.312 | 1.476 | 4.029 | 39.33 | 87.7 ± 11 | 9 |
| 3.................. | 10 35 37.9 | +57 57 15 | 3.060 | 1.476 | 8.422 | 19.09 | 77.0 ± 10 | 8 |
| 4.................. | 10 34 30.8 | +57 59 12 | 3.132 | 2.196 | 4.016 | 16.69 | 30.7 ± 6.6 | 8 |

$^a$ Off-axis angle in the field in which the source is detected.

$^b$ Defined as $(A/A_9)^{1/2}/r_9$, where $A$ is the area of the source region from the `vtpdetect` report and $r_9$ is the 99% PSF radius at the off-axis angle.

$^c$ Net counts reported by `vtpdetect`.

$^d$ Number of the LHNW field where the source has the smallest off-axis angle.

**Fig. 19**—Adaptively smoothed X-Ray images of the extended sources superposed on the deep $R$-band optical images.  
(a) Sources 1 and 2; (b) source 3; and (c) source 4.
being a blend of point sources. However, a bright gravitational lensing arc found in the optical image (see § 5.6) at the X-ray peak makes it very likely that the X-ray emission is associated with a cluster. Considering the nonuniformity of the detection due to vignetting and PSF effects, the number counts for extended sources above 3.7 × 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} are roughly greater than 10 \text{ deg}^{-2}. This agrees with the log N–log S relations of clusters at these fluxes found in the CDFs (Bauer et al. 2002). It is interesting to note that all four extended sources are found on only two of the overlapping ACIS-I fields in the north of the LHNW region.

5.2. Optical Imaging Observations

Optical observations are described in detail in S04. Optical images were obtained with Suprime-Cam on Subaru (in B, V, R, I, and z') and with the CFH12K camera on the CFHT (in R, B, and CFHT z'). The 2 \sigma limits in B, V, R, I, and z' are 27.8, 27.5, 27.9, 26.4, and 26.2, respectively.

X-ray contours superposed on R-band optical images are shown in Figure 19. We examined the number counts of galaxies within circular cells with fixed radii of 0.5. At a threshold of R < 24, a total of 19, 28, 18, and 9 galaxies were found within the cells centered at the X-ray peaks of each extended source. Because a star is found at 0.6 southeast of the X-ray peak of source 2, the galaxy counts could be underestimated. Compared with the expected 6.7 galaxies per cell obtained from the whole field, the overdensities of galaxies in sources 1

5

| Source Number | z_{RS} | z_{BCG} | z_{X-ray} |
|---------------|-------|--------|----------|
| 1             | 0.50  | 0.58 ± 0.08 | 0.5 ± 0.2 |
| 2             | 0.50  | 0.73 ± 0.08 | 0.5 ± 0.2 |
| 3             | ⋮     | 0.73 ± 0.08 | ⋮        |
| 4             | 0.45  | 0.45 ± 0.06 | ⋮        |
and 2 are more than 3 σ, whereas the overdensity of galaxies in source 3 is ∼3 σ. Source 4 does not show significant clustering of galaxies in the R-band image. Sources 1 and 2 are very close to each other, with a separation of ∼2′. The closeness and the elongated morphology of the two sources suggest that they are undergoing interactions. Source 3 is extended along the east-west direction with multiple peaks. All four sources show bright elliptical galaxies at the X-ray peaks.

5.3. X-Ray Spectra

We extract very coarse spectra (grouped to more than 15 counts per bin to allow the use of the χ^2 statistic) and attempt to constrain the properties of the clusters. We fitted the data with a simple MEKAL model in XSPEC (ver. 11.2), with a fixed abundance of 0.3 of the solar value and a fixed Galactic absorption. We restrict the spectral fitting to within 0.5–5 keV, because the signal-to-noise ratio is poor outside of this range.

The source extraction and background regions of sources 1 and 2 are shown in Figure 20. The regions avoid the point sources between the two clusters. The spectra are shown in Figure 21. For source 1, we found the best fit to be kT = 1.4^{+1.0}_{-0.2} keV and } = 0.5 ± 0.2, with a reduced χ^2 = 8.8 for nine degrees of freedom. This agrees with the redshift estimates using the optical data (Table 5). Fitting the same model to the spectrum of source 2 with the redshift fixed to } = 0.5 yields kT = 3.1^{+13.3}_{-1.6} keV, with a reduced χ^2 = 4.6 for nine degrees of freedom. The constraint on the temperature is poor, but the probability that the temperature of source 2 is significantly different than that of source 1 is low. This can be seen in Figure 22, where the joint probability contour of the temperature from the two sources is shown. The confidence level for the two sources having different temperatures is only 2 σ. Combining the two data sets and fixing } = 0.5, we find kT = 1.7^{+2.2}_{-0.5} keV.

The spectrum of source 3 shown in Figure 23 was extracted from a circular region with radius 36″. The background was extracted from an annulus with inner radius 36″ and outer radius 60″. The data cannot constrain the model very well, but a simple fit with an absorbed power law shows that the spectrum is very soft, with photon index Γ = 2.6 and reduced χ^2 = 7.2 for seven degrees of freedom. Fitting with a MEKAL model and assuming a redshift of } = 1.1 (see § 5.5), we obtain a temperature of 2.3^{+1.1}_{-0.8} keV with reduced χ^2 = 0.77. The temperature is insensitive to the redshift between } = 0.4 and 1.4. The fact that the MEKAL model fits the data better makes it less likely that source 3 is a blend of several point sources.

With only 30.7 net counts, it is impossible to model the spectrum for source 4. However, the source has very few counts above 2 keV, indicating that the temperature should be low if the source is at } > 0.4, as implied from the optical data.

The virial masses of the extended sources can be roughly estimated using the best-fit M-L relation (Finoguenov et al. 2001), M_{500} = 2.45 \times 10^{13} T^{1.87}, where M_{500} is the mass within a radius where the overdensity is 500. The results are shown in Table 6. All of the sources belong to low-mass clusters or groups, and this result is not very sensitive to the redshift because of the very soft spectra.

5.4. Angular Sizes

The angular sizes of the sources were quantified by the widths of the radial profiles. We fitted the radial profiles of the sources with integrated two-dimensional Gaussian curves, which describe the low signal-to-noise ratio data reasonably well. We constructed the cumulative counts as a function of off-source radius (curve of growth). Exposure maps were applied to correct for vignetting. Nearby point sources were removed and replaced with background noise. The background regions were selected visually and fitted with a quadratic form plus a constant. The curves of growth were then normalized to the best-fit backgrounds. The normalized curve of growth for each source is shown in Figure 24. This left only one parameter to be determined—the widths of the curves. The best-fit 1 σ radii are listed in Table 6.

5.5. Redshifts

We infer the redshifts of the extended sources using the red-sequence method, as well as the brightest cluster galaxy (BCG) method. Based on observations of clusters, there is usually a population of early-type galaxies that follows a color-magnitude relation (red sequence). This relation changes with redshift in a predictable way, such that a robust two-color photometric redshift can be obtained (Gladders & Yee 2000). Color-magnitude plots of the sources within 0.5 of the X-ray centers are shown for each extended source in Figure 25. Red sequences can be clearly seen in sources 1, 2, and 4. By
comparing with the models from Yee & Gladders (2001), we can estimate the redshifts for these three extended sources (Table 5). Source 3 does not show a clear red sequence.

BCGs are often used as distance indicators because they have almost constant luminosity (Humason et al. 1956). One of the difficulties in applying this method is that with optical images alone, it is hard to distinguish between the background and the cluster members unless a density peak can be clearly determined. In our case, this is less worrisome because bright spheroidal/lenticular galaxies are found at the X-ray peaks of all of the extended sources. This clearly associates these galaxies with the clusters. Furthermore, these galaxies are also the brightest early-type galaxies in the regions where X-ray emission is significant. Following Postman & Lauer (1995), we fit the radial profile of each of the BCGs to obtain the magnitudes within an angular radius $r_m$ and the slope of the profile ($\alpha \equiv d \log L_m / d \log r_m$), where $L_m$ is the luminosity within $r_m$. We visually examine the profile so that nearby galaxies are

| Source Number | $z_{\text{fit}}$ | $kT^a$ | $M_{500}$ | Core Radius | $f_{0.5-8\text{ keV}}$ | $L_{\text{bol}}$ |
|---------------|----------------|--------|-----------|-------------|--------------------|----------------|
| 1.............. | 0.50          | $1.4^{+0.8}_{-0.4}$ | $0.45^{+0.61}_{-0.21}$ | 12.9 | 1.6 | 2.2 |
| 2.............. | 0.50          | $3.1^{+0.5}_{-1.4}$ | $2.0^{+1.4}_{-0.4}$ | 17.0 | 1.2 | 1.5 |
| 3.............. | 0.73          | $2.3^{+1.8}_{-0.6}$ | $1.3^{+1.2}_{-0.4}$ | 14.7 | 1.5 | 5.1 |
| 4.............. | 0.45          | 1.0 (fixed)          | 0.24 | 11.8 | 0.42 | 0.45 |

* Listed are single-parameter $1 \sigma$ errors.

![Fig. 24a](image1.png)
![Fig. 24b](image2.png)
![Fig. 24c](image3.png)
![Fig. 24d](image4.png)

Fig. 24.—Curves of growth for the extended sources (sources 1–4 shown in panels a–d, respectively) normalized to the best-fit background. The dotted line shows the best fit of an integrated two-dimensional Gaussian.
not included in the aperture. The K-correction is performed using $K_R = 2.5 \log_{10}(1 + 0.96z)$. We then solve the redshifts for each galaxy by assuming the cosmological parameters given in §1. The resulting redshifts are listed in Table 5.

Although it appears that the BCG method produces higher redshifts than the red-sequence method, the differences are not significant, given the large uncertainties in both methods. The redshifts of sources 1 and 2 also agree with the spectral fitting results from the X-ray data.

The X-ray luminosities of the extended sources are listed in Table 6, assuming the red-sequence–determined redshifts, except for source 3, for which the BCG redshift is adopted. Within errors, the temperatures and luminosities of the sources agree with the scaling law found in high-redshift X-ray clusters (Ettori et al. 2003), but the constraint is weak.

5.6. Discovery of a Gravitational Lensing Arc

We have found a gravitational lensing arc close to source 3 (Fig. 26). The arc has an angular radius of $\sim 6''$. A bright spheroidal galaxy is clearly associated with the arc. A possible counterarc is seen connecting to the west of the bright galaxy but is not fully resolved. With $B$, $V$, $R$, $I$, and $z'$ observations, we can estimate photometric redshifts for the cD galaxy and the arc using the publicly available photometric redshift code hyperz (Bolzonella et al. 2000). We find photometric redshifts for the cD galaxy and the arc of $z = 0.45$ and 1.7, respectively. The redshift of the galaxy is slightly different than the redshift of the cluster obtained using the BCG method. From our experience, one often needs at least seven colors to obtain a secure photometric redshift. The redshift estimates therefore need verification. We now discuss the estimated lensing properties.
If the source is at $z_{\text{src}} \sim 0.45$ and the arc is at $z_{\text{arc}} \sim 1.7$, then we can estimate the mass within the Einstein radius (reasonably approximated by the radius of the arc) as

$$M(\theta < \theta_E) = 1.1 \times 10^{14} \left(\frac{\theta}{30''}\right)^2 \left(\frac{D_L D_S}{D_S}\right) M_\odot,$$

where $D_L$, $D_S$, and $D_{LS}$ are, respectively, the angular diameter distances (in gigaparsecs) of the lens, source, and the distance between the lens and source. With $z_{\text{arc}} \sim 0.45$ and $z_{\text{src}} \sim 1.7$, we obtain $M(\theta < \theta_E) \sim 3.3 \times 10^{12} M_\odot$. We compare this mass with what would be expected if the source were a group of galaxies at $z = 0.45$, assuming the mass profiles are self-similar. By fixing the redshift, the X-ray spectra yield a temperature of 2.2 keV. The virial radius is roughly $r_{500} = 0.63(kT)^{1/2}$ = 955 kpc (Finoguenov et al. 2001), where $r_{500}$ is defined as the radius within which the overdensity is 500. The size of the arc at $z \sim 0.45$ is $\Delta r_{\text{arc}} \sim 37$ kpc = 0.036$r_{500}$. Compared with the mass profiles of NGC 2563, NGC 4325, and NGC 2300 (Mushotzky et al. 2003), the mass inside the Einstein radius agrees very well with that of a group of galaxies. The virial mass of the group can then be estimated to be $\sim 1.2 \times 10^{14} M_\odot$ (Finoguenov et al. 2001).

If the cluster is at $z \sim 0.7$, as implied from the BCG method, and if the best-fit temperature $kT = 0.23$ keV is assumed, then we can search for the best redshift of the lensed galaxy so that the mass within the Einstein radius agrees with the mass profile of groups. We find that if the lensed galaxy is at $z = 1.8$, then the mass within the Einstein radius is $M(\theta < \theta_E) \sim 3 \times 10^{12} M_\odot$, which fits the mass profile of groups.

If the redshift estimate is correct, then the arc system is very similar to the one discovered in the ROSAT deep survey of the Lockman Hole (Hasinger et al. 1998). High-redshift gravitational lensing arcs are, so far, rarely observed objects. However, since our large-area survey is very similar in sky area and depth to the ROSAT Deep Survey and since both have produced a detection of a strong arc, the probability of detection seems high. Larger area surveys of X-ray-selected clusters of galaxies with deep optical follow-up would help to determine the probability of detection. Such observations should put useful constraints on $\Omega_m$ and on the density of galaxies at high redshifts (Cooray 1999).

It is interesting to note that all four of our clusters may have redshifts $z \sim 0.4$–0.5 and are located within a region of only $\sim 20'$ in the northeast corner of our field. This corresponds to a comoving radius of $\sim 5$ Mpc. The implications of such large-scale structure on the CXB need to be investigated further.

6. SUMMARY

In this paper, we presented our CLASXS X-ray catalog. Our survey covers a $\sim 0.4$ deg$^2$ contiguous area in an uniform manner and reaches fluxes of $5 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.4–2 keV band and $3 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ in the 2–8 keV band. We found a total of 525 point sources and four extended sources. We summarize our results as follows.

1. The number counts in the 0.4–2 keV band agree very well with other large-area surveys. On the other hand, the number counts in the 2–8 keV band deviate significantly from other large-area surveys at the “knee” of the log $N$–log $S$ relation, possibly as a result of the underlying large-scale structure. The total 2–8 keV band flux agrees with the observed CXB flux within the observed variance of the CXB, indicating that the true normalization of the CXB can be determined using fields with solid angles $\sim 0.3$–0.4 deg$^2$.

2. The hardness ratios of the sources in the CLASXS field show a significant change at $f_{2–8} \sim 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, which bridges the range sampled by previous studies and confirms the results found in deep Chandra/XMM-Newton surveys. About 60% of the sources with full-band fluxes greater than $4 \times 10^{-14}$ show significant variability, whereas the fraction drops dramatically with decreasing flux, partly because of selection effects. Most sources show no change of hardness ratio or anti-correlation with flux, but some sources show a positive correlation or mixed trends.

3. We report on the X-ray and multicolor analysis of four extended sources. We argue that the sources are likely low-mass clusters or groups at redshifts $\sim 0.5$. Two of the clusters are probably interacting or merging.

4. We report on the discovery of a gravitational lensing arc. The lensing cluster is consistent with being at a redshift of $z = 0.45$–0.7.

We thank Jean Swank for the suggestion of C-statistics, Ann Horschemeier for discussions on wavdetect, and an anonymous referee for comments that helped to improve the paper. Y. Y. also thanks Chris Reynolds for his encouragement and help during this thesis work. This paper would not have been possible without the excellent work of the supporting staff at CXC and the superb instrument of the Chandra X-Ray Observatory.

This project was partially funded under the IDS program of R. Mushotzky. We also gratefully acknowledge support from NASA’s National Space Grant College and Fellowship Program and the Wisconsin Space Grant Consortium (A. T. S.), CXC grant GO2-3191A (A. J. B.), NSF grants AST-0084847 and AST-0239425 (A. J. B.) and AST-0084816 (L. L. C.), and the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, the Alfred P. Sloan Foundation, and the David and Lucile Packard Foundation (A. J. B.). This paper is part of Y. Y.’s Ph.D. thesis work at the University of Maryland.

REFERENCES

Akiyama, M., Ueda, Y., Ohta, K., Takahashi, T., & Yamada, T. 2003, ApJS, 148, 275
Alexander, D. M., et al. 2003, AJ, 126, 539
Alexander, D. M., Brandt, W. N., Horschemeier, A. E., Garmire, G. P., Schneider, D. P., Bauer, F. E., & Griffiths, R. E. 2001, AJ, 122, 2156
Baldi, A., Molendi, S., Comastri, A., Fiore, F., Matt, G., & Vignali, C. 2002, ApJ, 564, 190
Barger, A. J., et al. 2003, AJ, 126, 632
Barger, A. J., Cowie, L. L., Mushotzky, R. F., & Richards, E. A. 2001, AJ, 121, 662
Barr, P. 1986, MNRAS, 223, 29P
Bauer, F. E., et al. 2002, AJ, 123, 1163
Bolzonella, M., Miralles, J.-M., & Pelló, R. 2000, A&A, 363, 476
Brandt, W. N., et al. 2001, AJ, 122, 2810
Cash, W. 1979, ApJ, 228, 939
Cooray, A. R. 1999, ApJ, 524, 504
Cowie, L. L., Garmire, G. P., Bautz, M. W., Barger, A. J., Brandt, W. N., & Horschemeier, A. E. 2002, ApJ, 566, L5
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Ettori, S., Tozzi, P., & Rosati, P. 2003, A&A, 398, 879
Finoguenov, A., Reiprich, T. H., & Böhringer, H. 2001, A&A, 368, 749
Freeman, P. E., Kashyap, V., Rosner, R., & Lamb, D. Q. 2002, ApJS, 138, 185
Gehrels, N. 1986, ApJ, 303, 336
Giacconi, R., et al. 2002, ApJS, 139, 369
Gladders, M. D., & Yee, H. K. C. 2000, AJ, 120, 2148
Harrison, F. A., Eckart, M. E., Mao, P. H., Helfand, D. J., & Stern, D. 2003, ApJ, 596, 944
Hasinger, G. 2004, in The Restless High Energy Universe, ed. E. P. J. van den Heuvel, J. J. M. in ’t Zand, & R. A. M. J. Wijers, Nucl. Phys. B Proc. Suppl., 132, 86
Hasinger, G., et al. 1998, A&A, 340, L27
Humason, M. L., Mayall, N. U., & Sandage, A. R. 1956, AJ, 61, 97
Kawara, K., et al. 2004, A&A, 413, 843
Kim, D.-W., et al. 2004, ApJS, 150, 19
Kushino, A., Ishisaki, Y., Morita, U., Yamasaki, N. Y., Ishida, M., Ohashi, T., & Ueda, Y. 2002, PASJ, 54, 327
Moretti, A., Campana, S., Lazzati, D., & Tagliaferri, G. 2003, ApJ, 588, 696 (M03)
Mushotzky, R. F., Cowie, L. L., Barger, A. J., & Arnaud, K. A. 2000, Nature, 404, 459
Mushotzky, R. F., Figueroa-Feliciano, E., Loewenstein, M., & Snowden, S. L. 2003, preprint (astro-ph/0302267)
Nandra, K., George, I. M., Mushotzky, R. F., Turner, T. J., & Yaqoob, T. 1997, ApJ, 476, 70
Piconcelli, E., Cappi, M., Bassani, L., Di Cocco, G., & Dadina, M. 2003, A&A, 412, 689
Piconcelli, E., Cappi, M., Bassani, L., Fiore, F., Di Cocco, G., & Stephen, J. B. 2002, A&A, 394, 335
Postman, M., & Lauer, T. 1995, ApJ, 440, 28
Revnivtsev, M., Gilfanov, M., Sunyaev, R., Jahoda, K., & Markwardt, C. 2003, A&A, 411, 329
Schmidt, M., et al. 1998, A&A, 329, 495
Steffen, A. T., Barger, A. J., Capak, P., Cowie, L. L., Mushotzky, R. F., & Yang, Y. 2004, AJ, 128, 1483 (S04)
Tozzi, P., et al. 2001, ApJ, 562, 42
Vikhlinin, A., Forman, W., Jones, C., & Murray, S. 1995, ApJ, 451, 553
Yang, Y., Mushotzky, R. F., Barger, A. J., Cowie, L. L., Sanders, D. B., & Steffen, A. T. 2003, ApJ, 585, L85
Yee, H. K. C., & Gladders, M. D. 2002, in ASP Conf. Ser. 257, AMiBA 2001: High-z Clusters, Missing Baryons, and CMB Polarization, ed. L.-W. Chen, C.-P. Ma, K.-W. Ng, & U.-L. Pen (San Francisco: ASP), 109