IMAGING LARGE SCALE STRUCTURE IN THE X-RAY SKY

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ABSTRACT

We present the first results from a wide solid angle, moderately deep Chandra survey of the Lockman Hole North-West region. Our 9 ACIS-I fields cover an effective solid angle of 0.4 deg\textsuperscript{2} and reach a depth of $3 \times 10^{-16}$ erg cm\textsuperscript{-2}s\textsuperscript{-1} in the 0.4–2 keV band and $3 \times 10^{-15}$ erg cm\textsuperscript{-2}s\textsuperscript{-1} in the 2–8 keV band. The best fit logN-logS for the entire field, the largest contiguous Chandra field yet observed, matches well onto that of the Chandra Deep Field North. We show that the full range of the ‘cosmic variance’ previously seen in different Chandra fields is reproduced in this small region of the sky. Counts-in-cells analysis shows that the hard band sources are more strongly correlated than the soft band sources.

Subject headings: cosmology: observations — large-scale structure of the universe — x-rays: diffuse background — galaxies: nuclei

1. INTRODUCTION

Recent Chandra and XMM observations have resolved over 85\% of the 2–8 keV X-ray background (XRB) into discrete sources, presumably active galactic nuclei (AGNs; Mushotzky et al. 2000; Brandt et al. 2001; Tozzi et al. 2001; Campana et al. 2001; Cowie et al. 2002; Giacconi et al. 2002; Hasinger et al. 2001). However, the nature of the sources is unclear, with many of the faint sources showing little or no optical activity (Barger et al. 2001, 2002; Hornschemeier et al. 2001; Rosati et al. 2002). There is a large field-to-field variance in the source counts in the Chandra deep surveys in the 2–8 keV band (Cowie et al. 2002). This cosmic variance is generally believed to arise from the underlying large-scale structure (LSS) that is traced, in some fashion, by the Chandra sources. Clustering of the XRB sources in redshift space has been seen in both Chandra Deep Fields (Barger et al. 2002; Hasinger 2002), indicating that LSS does exist in the XRB source distribution.

From a cosmological point of view, AGNs are expected to be highly biased tracers of cosmic structure formation at medium to large redshifts. The XRB sources, which have $\sim 10$ times the areal density of optically selected AGNs, provide for the first time a sufficiently high density to be used as tracers of the LSS.

The clustering at various scales of X-ray selected AGNs has been pursued previously using observations from HEAO-1 (e.g. Barcons & Fabian 1988; Mushotzky & Jahoda 1992) and ROSAT (e.g. Soltan et al. 1997; Vikhlinin & Forman 1995). The ROSAT results based on deep pointings (Carrera et al. 1998) show a much smaller amplitude of correlation than predicted from optical samples, while an analysis of the ROSAT North Ecliptic Pole sample, which is shallower but covers a wider solid angle (Mullis 2002), comes to the opposite conclusion. It has been claimed that at a flux level below $1.5 \times 10^{-15}$ erg cm\textsuperscript{-2}s\textsuperscript{-1} (0.5–2 keV) the XRB exhibits no clustering (Soltan & Hasinger 1994). This contradicts the observed cosmic variance in the ultradeep surveys by Chandra and XMM. How to combine these seemingly disparate results is one of the new mysteries of the XRB.

To allow a direct measurement of the auto-correlation functions (ACFs) of the XRB sources, and to optically identify these objects to obtain their redshifts, one needs arcsecond spatial resolution, a wide contiguous field of view, and sufficient sensitivity. To achieve these goals we have performed a large solid angle, moderately deep Chandra survey of the Lockman Hole North-West region. This survey currently has a contiguous sky coverage of $\sim 0.4$ deg\textsuperscript{2} and is sensitive to X-ray flux levels of $3 \times 10^{-16}$ erg cm\textsuperscript{-2}s\textsuperscript{-1} (0.4–2 keV) and $3 \times 10^{-15}$ erg cm\textsuperscript{-2}s\textsuperscript{-1} (2–8 keV). Most of the XRB is resolved at these flux levels (Cowie et al. 2002).

2. OBSERVATIONS AND DATA REDUCTION

The survey covers the Lockman Hole North-West region centered at $\alpha = 10^h34^m, \delta = 57^\circ40^\prime$ (J2000). The region has very low Galactic column density ($N_H \approx 5.72 \times 10^{19}$ cm\textsuperscript{-2}, Dickey & Lockman 1990) and was covered by the deepest 170$\mu$m ISOPHOT field observed from ISO (hereafter ISONW). The field has also been observed at 850$\mu$m with the SCUBA camera on the James Clerk Maxwell Telescope and at cm wavelengths with the VLA, as well as at optical and near-IR wavelengths with the Subaru (using the unique Suprime-Cam instrument) and Keck telescopes. The ISONW region will be intensively observed with SIRTF as part of the LEGACY program. The multiwavelength analysis of this field will be presented in subsequent papers.

The observation consists of 9 ACIS-I pointings (labeled as ISONW1–ISONW9) separated from each other by $\sim 10^\prime$ to allow close to uniform sky coverage. ISONW1 has an exposure time of $\sim 70$ ks while the other 8 pointings have...
Fig. 1.— The cumulative number counts in the 9 fields (a), (b) and the whole field (c), (d). For each (a) and (b), the insert shows the number counts of each ISONW field at flux level of $2 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}$ (soft) and $9 \times 10^{-15} \text{erg cm}^{-2} \text{s}^{-1}$ (hard). The solid line is the logN-logS of CDF-N. Field numbers 10 and 11 represents the CDF-N and CDF-S value respectively. The highest counts in the 9 fields are about 2.3 (soft) and 3.3 (hard) times higher than that from CDF-S, which has the lowest normalization among all the deep surveys (Cowie et al. 2002). For the hard band, number counts of 8 of the 9 fields are $\sim 1\sigma$ about the mean, but ISONW5 is much lower. For each (c) and (d), cumulative number counts for the whole field (diamonds with solid lines representing the Poisson error) is compared with that from CDF-N (solid histogram), CDF-S (dash-dotted histogram) and SSA13 (dashed line). The inserts shows the sensitive sky area vs flux.

exposure times of $\sim 40$ ks.

The data were reduced with CIAO 2.2.1 and CALDB 2.15. The CXC Science Threads were followed in data preparation. The resulting event lists were binned into 2 energy bands, the soft (0.4–2 keV) and the hard (2–8 keV).

Point sources were detected for each pointing in both energy bands with wavdetect within the CIAO package. The wavelet scales of square root series 1, $\sqrt{2}$, 2, $\sqrt{2}$, 4, $\sqrt{2}$, 8 and a false detection threshold of $1 \times 10^{-7}$ were used. Spectrally weighted monochromatic exposure maps were created, assuming a power law with photon index of 1.2 for the hard band and 1.4 for the soft band (Mushotzky et al. 2000; Barger et al. 2001). Count rates were converted to flux assuming the above power law spectra with only Galactic absorption. The conversion factors are $4.74 \times 10^{-12} \text{erg cm}^{-2}$ (soft) and $2.34 \times 10^{-11} \text{erg cm}^{-2}$ (hard). The degradation of the ACIS low energy quantum efficiency during the flight was corrected using the measurements of the ACIS team.

The catalogs for all observations were merged. Source properties for objects detected in more than one observation (due to the overlapping of fields) were taken from the field in which the source had the smallest off-axis angle. In the soft band, 431 sources were detected, and in the hard band, 278. The combined catalog contains 554 sources.

3. ANALYSIS AND RESULTS

Since the effective area decreases and the point spread function (PSF) increases with off-axis angle, the sensitivity is not uniform across the field. We quantified this with Monte-Carlo simulations. First we constructed background maps by removing the wavelet detected sources from the observed images and filled the holes with Poisson noise sampled from regions surrounding the sources. Sources with fluxes drawn from the LogN-LogS derived from the Chandra deep fields (Cowie et al. 2002; Garmire 2002) were generated and distributed uniformly within 8' from the aim point. PSF images of each source were made using mkpsf. The exposure maps described in the previous section were then applied to simulate the effect of vignetting. The simulated sources were added to the background maps to create simulated images. About 100 simulations were performed for each band and exposure (for details see Yang et al. 2003). Above flux thresholds of 10 cts/exposure (soft) and 12 cts/exposure (hard), the detection is complete and the derived fluxes are consistent with the input values. We use the flux unit in cts/exposure because we found the wavdetect exposure-corrected count rates threshold in such unit only depends weakly on the exposure time in our observations due to the low backgrounds. We obtain the same results by assuming a uniform background and the wavdetect detection thresholds described in Freeman et al. (2002). Within 4.5' of the aim
point, the detection is complete above 5 cts/exposure in
the soft band and 7 cts/exposure in the hard band.

Above flux thresholds of $1.2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (soft) and $8 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (hard), the source catalog in
the combined field within 8’ from each aim point is com-
plete. This defines a flux limited sample that contains 115
hard band and 298 soft band sources. The solid angle
covered by the complete sample field is 0.33 deg$^2$.

We constructed the cumulative number counts (LogN-
LogS) for each of 9 fields, as well as the whole merged
catalog (Fig. 1). The Eddington bias found at these flux
levels from the simulations is small and can be ignored.

A sketch of the flux limited sample (region out-
lined with a dashed line). The maps have been adaptively smoothed
using fadapt in FTOOLS with a 6 counts kernel counts threshold.

The gray scale map represents the source density in the soft band.
The contours shows the source density in the hard band. The 7 con-
tour levels are proportional to the logarithm of the source densities.

Fig. 1a and 1b show comparisons of the LogN-LogS in
the 9 pointings. Although the overlapping of fields could
minimize the differences between them, this is the simplest
way to demonstrate the cosmic variance because exactly
the same procedures were used in each field and 8 of the 9
fields have virtually identical exposures. Variance is seen
in both the soft and hard bands. The full range of variance
seen in the Chandra deep surveys published to date is
reproduced in this set of contiguous fields.

The LogN-LogS of the whole field is compared with
that from Chandra deep field North (CDF-N; Brandt et
al. 2001), the Chandra Deep Field south (CDF-S, Rosati et
al. 2001) and SSA13 (Mushotzky et al. 2000) in Fig. 1c
and 1d. Our LogN-LogS connects smoothly with that of
CDF-N, which has the highest normalization of all the
published Chandra deep fields.

The LogN-LogS distribution of the combined fields is
modeled with power laws in the form of $N(>S) = A(S/S_0)^{-\alpha}$, using the area weighted maximum likelihood
method (Murdoch, Crawford & Jauncey 1973). For the
soft band, between $2 \times 10^{-15}$ and $10^{-14}$ erg cm$^{-2}$ s$^{-1}$, $A =
630, S_0 = 2 \times 10^{-15}$, and $\alpha = 0.72 \pm 0.18$; above $1 \times 10^{-14}$
erg cm$^{-2}$ s$^{-1}$, $A = 152, S_0 = 1 \times 10^{-14}$, and $\alpha = 1.58 \pm
0.23$. For the hard band above $1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, the
best fit parameters are $A = 359, S_0 = 1 \times 10^{-14}$, and $\alpha =
1.56 \pm 0.16$.

To visualize the source distributions, we used adaptive
smoothing to create density maps of the flux limited sample
(Fig.2). Structure is visible in both the soft and hard
band maps, but the hard band sources are more clustered.
To test whether the observed over-density could arise from
Poisson fluctuations, we employed the likelihood test de-
scribed in Carrera et al.(1998). Comparing with 10000
simulated samples which are Poisson distributed, we found
97.67% of the soft and 99.99% of the hard band simulations
had better likelihood than the observations. The signifi-
cance of clustering is therefore 2$\sigma$ (soft) and 4$\sigma$ (hard).

Using the source distribution in cells tiling the field
(counts-in-cells), we can estimate the correlation scales
of the sources. The variance of counts-in-cells defined as
$\mu_2 \equiv \langle (N - \bar{N})^2 \rangle$, where $\bar{N}$ is the mean counts in the
cell, is directly related to the angular correlation function
(Peebles 1980) by

$$\mu_2 = \bar{N} + \frac{\bar{N}^2}{\Omega} \int w(\theta) d\Omega_1 d\Omega_2$$ (1)

where $\Omega$ is the cell size. The first term is the Poisson
fluctuation. For correlation functions with a power-law form
$w(\theta) = (\theta/\theta_0)^{1-\gamma}$ (where $\gamma$ is the power law index
of the spatial correlation function) and square cells with
size $\Omega = \Theta \times \Theta$ deg$^2$, the integration can be obtained as
(Totsuji & Kihara 1969; Lahav & Saslaw, 1992),

$$\sigma^2 \equiv \frac{\mu_2 - \bar{N}}{(N/\Omega)^2} = C_{\gamma} \theta_0^{1-\gamma} \Theta^{5-\gamma}$$ (2)

where $\sigma^2$ is the normalized variance. $C_{\gamma}$ is a function of $\gamma$
and is calculated numerically. We calculate $\sigma^2$ for square
cells of various sizes that tile the whole field. By fitting
the $\sigma^2 - \Theta$ relation we should be able to estimate $\theta_0$ and $\gamma$.
We found the present data cannot constrain both param-
ters accurately. By fixing $\gamma = 1.8$, the “universal” slope
measured in galaxies and in groups and clusters of galaxies
(Bahcall 1988), and minimizing $\chi^2$, we found $\theta_0 = 40 \pm 11''$
and $\theta_0 = 4 \pm 2''$ for the hard and soft band sources respec-
respectively. While the hard band sources agree very well with the angular correlation scale previously seen in ROSAT sur-
veys (Vikhlinin & Forman, 1995), the hard band sources are
much more strongly correlated.

The striking difference in clustering between the soft and
hard band sources indicates the hard sources which are
not detected in the soft band are highly clustered. About
60% of the hard-band-only sources lie in overdense regions
which form a ‘band’ connecting the ‘lumps’ on the west-
ern and eastern side of the field (Fig. 2). This band in-
cludes only about 1/3 of solid angle of the whole field. The
counts-in-cells analysis (Fig. 3) also indicates that these
hard-band-only sources have larger correlation scales than
the soft band or hard band sources.

4. DISCUSSION

ASCA observations have shown that the rms variance of
the 2–10 keV XRB on a scale of 0.5 deg$^2$ is $\approx 6\%$ (Kushino
et al. 2002). With a sky coverage of 0.4 deg$^2$ and a depth
that resolves $>50\%$ of the hard band XRB, the normalization of LogN-LogS derived from our observations should be very close to the “true” value. The fact that the observed LogN-logS connects onto the CDF-N field at low fluxes then indicates that $>90\%$ of the XRB is resolved using the ASCA/ROSAT XRB normalization (Chen et al. 1997). The main uncertainty is the normalization of XRB itself.

The LSS seen in our field has reproduced the cosmic variance observed previously in deep field surveys. It is noticeable (Fig. 1b) that on scales of a Chandra field the variance is demonstrated as holes rather than lumps, i.e., the number counts in 9 fields are close to the mean, while only 2 field have very low value (ISONW5 & CDF-S). This indicates the existence of voids in the X-ray LSS, which should, within a factor of a few, be of the same angular size as an ACIS-I field. Most of the hard-band-only sources cluster in relatively small regions, which may be topologically connected. If this is not a result of a projection effect, then it is the first time a wall-like structure has been seen in the X-ray sky.

We have found more variance in the hard band than in the soft band, consistent with the lower mean redshift of the hard X-ray sources. However, the difference in the mean redshift cannot account for most of the large difference in the soft and hard band angular correlation length found by the counts-in-cells statistic. The mean redshift found previously for the Chandra/XMM deep fields sources is $\sim 0.8$. Unless most of the hard band sources are at very low redshift, which does not seem likely because we see no low redshift spikes in the redshift distribution of deep field surveys, the relatively low redshifts for the hard X-ray selected sources could not account for the factor of 10 larger differences in correlation scales seen in these sources. The similarity of the redshift distributions for the sources found in CDF-N and in an observation with a similar exposure to ours (Castander et al. 2003), indicates that the luminosity functions have likely been sampled below the “knee” for all redshifts in our observations. Thus we feel that the stronger correlation function for the hard sources seen in our data is likely due to their stronger spatial correlation rather than a redshift effect.

The large variance in the Chandra source counts indicates that they must be highly biased tracers of matter. Direct calculation of the bias will require redshifts and an understanding of how the luminosity function changes with redshift, but it is already clear that the Chandra sources show much more variance than galaxy counts (Cohen et al. 2000) at similar optical magnitudes.

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Figure 3.— Normalized variance $\sigma^2$ measured with different sized square cells which tiles the whole field. Squares: the hard band sources; triangles: the soft band sources. Crosses: the hard band only sources. The errors are estimated via a boots-trap technique. The lines shows the best fit variance with $\gamma = 1.8$ (fixed) and $\theta_0 = 40'' \pm 11$ for the hard band, $\theta_1 = 4'' \pm 2$ for the soft band sources. The hard-band-only points are not fitted due to the small number of sources.

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