

## THE *CHANDRA* DEEP FIELD–SOUTH SURVEY: 2 Ms SOURCE CATALOGS

B. LUO,<sup>1</sup> F. E. BAUER,<sup>2</sup> W. N. BRANDT,<sup>1</sup> D. M. ALEXANDER,<sup>3</sup> B. D. LEHMER,<sup>3</sup> D. P. SCHNEIDER,<sup>1</sup> M. BRUSA,<sup>4,5</sup>  
A. COMASTRI,<sup>6</sup> A. C. FABIAN,<sup>7</sup> A. FINOGENOV,<sup>4,5</sup> R. GILLI,<sup>6</sup> G. HASINGER,<sup>4</sup> A. E. HORNSCHEMEIER,<sup>8</sup>  
A. KOEKEMOER,<sup>9</sup> V. MAINERI,<sup>10</sup> M. PAOLILLO,<sup>11</sup> P. ROSATI,<sup>10</sup> O. SHEMMER,<sup>1</sup> J. D. SILVERMAN,<sup>12</sup>  
I. SMAIL,<sup>13</sup> A. T. STEFFEN,<sup>14</sup> AND C. VIGNALI<sup>15</sup>

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### ABSTRACT

We present point-source catalogs for the  $\approx 2$  Ms exposure of the *Chandra* Deep Field–South (CDF-S); this is one of the two most sensitive X-ray surveys ever performed. The survey covers an area of  $\approx 436$  arcmin<sup>2</sup> and reaches on-axis sensitivity limits of  $\approx 1.9 \times 10^{-17}$  and  $\approx 1.3 \times 10^{-16}$  ergs cm<sup>-2</sup> s<sup>-1</sup> for the 0.5–2.0 and 2–8 keV bands, respectively. Four hundred and sixty-two X-ray point sources are detected in at least one of three X-ray bands that were searched; 135 of these sources are new compared to the previous  $\approx 1$  Ms CDF-S detections. Source positions are determined using centroid and matched-filter techniques; the median positional uncertainty is  $\approx 0.36''$ . The X-ray-to-optical flux ratios of the newly detected sources indicate a variety of source types;  $\approx 55\%$  of them appear to be active galactic nuclei, while  $\approx 45\%$  appear to be starburst and normal galaxies. In addition to the main *Chandra* catalog, we provide a supplementary catalog of 86 X-ray sources in the  $\approx 2$  Ms CDF-S footprint that was created by merging the  $\approx 250$  ks Extended *Chandra* Deep Field–South with the CDF-S; this approach provides additional sensitivity in the outer portions of the CDF-S. A second supplementary catalog that contains 30 X-ray sources was constructed by matching lower significance X-ray sources to bright optical counterparts ( $R < 23.8$ ); the majority of these sources appear to be starburst and normal galaxies. The total number of sources in the main and supplementary catalogs is 578. Optical *R*-band counterparts and basic optical and infrared photometry are provided for the X-ray sources in the main and supplementary catalogs. We also include existing spectroscopic redshifts for 224 of the X-ray sources. The average backgrounds in the 0.5–2.0 and 2–8 keV bands are 0.066 and 0.167 counts Ms<sup>-1</sup> pixel<sup>-1</sup>, respectively, and the background counts follow Poisson distributions. The effective exposure times and sensitivity limits of the CDF-S are now comparable to those of the  $\approx 2$  Ms *Chandra* Deep Field–North (CDF-N). We also present cumulative number counts for the main catalog and compare the results to those for the CDF-N. The soft-band number counts for these two fields agree well with each other at fluxes higher than  $\approx 2 \times 10^{-16}$  ergs cm<sup>-2</sup> s<sup>-1</sup>, while the CDF-S number counts are up to  $\approx 25\%$  smaller than those for the CDF-N at fluxes below  $\approx 2 \times 10^{-16}$  ergs cm<sup>-2</sup> s<sup>-1</sup> in the soft band and  $\approx 2 \times 10^{-15}$  ergs cm<sup>-2</sup> s<sup>-1</sup> in the hard band, suggesting small field-to-field variations.

*Subject headings:* cosmology: observations — diffuse radiation — galaxies: active — surveys — X-rays: galaxies

*Online material:* extended figure, color figure, machine-readable tables

### 1. INTRODUCTION

One of the greatest successes of the *Chandra X-Ray Observatory* (*Chandra*) has been the characterization of the sources creating the 0.5–8 keV cosmic X-ray background, and the deepest *Chandra* surveys form a central part of this effort. The two deepest *Chandra* surveys, the *Chandra* Deep Field–North and *Chandra* Deep Field–South (CDF-N and CDF-S, jointly CDFs; see Brandt & Hasinger 2005 for a review), have each detected hundreds of X-ray sources over  $\approx 450$  arcmin<sup>2</sup> areas with enormous multi-wavelength observational investments. They have measured the highest sky density of accreting supermassive black holes to date and have also enabled novel X-ray studies of starburst and normal

galaxies, groups and clusters of galaxies, large-scale structures in the distant universe, and Galactic stars.

As part of an effort to create still deeper X-ray surveys, we proposed for substantial additional exposure on the CDF-S during *Chandra* Cycle 9. The CDF-S has superb and improving coverage at optical, infrared, and radio wavelengths; it will continue to be a premiere multiwavelength deep-survey field for the coming decades as additional large facilities are deployed in the southern hemisphere. Furthermore, owing to the 1 Ms of *Chandra* exposure already available (Giacconi et al. 2002, hereafter G02), the CDF-S is a natural field to observe more sensitively. Although our proposal was not approved in the peer review, 1 Ms of Director’s Discretionary Time was subsequently allocated for deeper CDF-S

<sup>1</sup> Department of Astronomy and Astrophysics, 525 Davey Lab, Pennsylvania State University, University Park, PA 16802.

<sup>2</sup> Columbia Astrophysics Laboratory, Columbia University, Pupin Laboratories, 550 West 120th Street, New York, NY 10027.

<sup>3</sup> Department of Physics, Durham University, Durham DH1 3LE, UK.

<sup>4</sup> Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, D-85748 Garching bei München, Germany.

<sup>5</sup> University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250.

<sup>6</sup> INAF–Osservatorio Astronomico di Bologna, Via Ranzani 1, I-04127 Bologna, Italy.

<sup>7</sup> Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK.

<sup>8</sup> Laboratory for X-ray Astrophysics, NASA Goddard Space Flight Center, Code 662, Greenbelt, MD 20771.

<sup>9</sup> Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.

<sup>10</sup> European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany.

<sup>11</sup> Dipartimento de Scienze Fisiche, Università di Napoli, Via Cinthia, 80126 Naples, Italy.

<sup>12</sup> ETH Zurich, Institute of Astronomy, Department of Physics, Wolfgang-Pauli-Strasse 16, 8093 Zurich, Switzerland.

<sup>13</sup> Institute of Computational Cosmology, Durham University, Durham DH1 3LE, UK.

<sup>14</sup> *Spitzer* Science Center, California Institute of Technology, Mail Code 220-6, 1200 East California Boulevard, Pasadena, CA 91125.

<sup>15</sup> Università di Bologna, Via Ranzani 1, I-04127 Bologna, Italy.

TABLE 1  
JOURNAL OF *Chandra* DEEP FIELD-SOUTH OBSERVATIONS

OBS. ID	OBS. START (DATE, UT)	EXPOSURE TIME <sup>a</sup> (ks)	AIM POINT <sup>b</sup>		ROLL ANGLE <sup>c</sup> (deg)	OBS. MODE <sup>d</sup>	PIPELINE VERSION <sup>e</sup>
			$\alpha$ (J2000.0)	$\delta$ (J2000.0)			
1431-0	1999 Oct 15, 17:38	24.6	03 32 29.44	-27 48 21.8	47.3	VF	R4CU5UPD11
1431-1	1999 Nov 23, 02:30	93.6	03 32 29.44	-27 48 21.8	353.9	F	R4CU5UPD11
441	2000 May 27, 01:18	56.0	03 32 26.91	-27 48 19.4	166.7	F	7.6.10
582	2000 Jun 03, 02:38	130.6	03 32 26.97	-27 48 18.5	162.9	F	7.6.10
2406	2000 Dec 10, 23:35	29.7	03 32 28.33	-27 48 36.5	332.2	F	7.6.10
2405	2000 Dec 11, 08:14	59.6	03 32 28.82	-27 48 43.5	331.8	F	7.6.10
2312	2000 Dec 13, 03:28	123.7	03 32 28.28	-27 48 36.9	329.9	F	7.6.10
1672	2000 Dec 16, 05:07	95.1	03 32 28.73	-27 48 44.5	326.9	F	7.6.10
2409	2000 Dec 19, 03:55	69.0	03 32 28.08	-27 48 38.6	319.2	F	7.6.10
2313	2000 Dec 21, 02:08	130.4	03 32 28.08	-27 48 38.6	319.2	F	7.6.10
2239	2000 Dec 23, 17:28	130.8	03 32 28.08	-27 48 38.6	319.2	F	7.6.10
8591	2007 Sep 20, 05:26	45.4	03 32 28.20	-27 48 06.9	72.7	VF	7.6.11.1
9593	2007 Sep 22, 20:34	46.4	03 32 28.20	-27 48 06.9	72.7	VF	7.6.11.1
9718	2007 Oct 03, 13:56	49.4	03 32 28.61	-27 48 07.4	62.0	VF	7.6.11.1
8593	2007 Oct 06, 02:04	49.5	03 32 28.61	-27 48 07.4	62.0	VF	7.6.11.1
8597	2007 Oct 17, 07:07	59.3	03 32 29.25	-27 48 10.4	44.2	VF	7.6.11.2
8595	2007 Oct 19, 14:16	115.4	03 32 29.35	-27 48 11.2	41.2	VF	7.6.11.2
8592	2007 Oct 22, 12:14	86.6	03 32 29.62	-27 48 13.8	32.4	VF	7.6.11.2
8596	2007 Oct 24, 13:20	115.1	03 32 29.62	-27 48 13.8	32.4	VF	7.6.11.2
9575	2007 Oct 27, 05:43	108.7	03 32 29.62	-27 48 13.8	32.4	VF	7.6.11.2
9578	2007 Oct 30, 22:35	38.6	03 32 29.84	-27 48 16.7	24.2	VF	7.6.11.2
8594	2007 Nov 01, 11:51	141.4	03 32 29.84	-27 48 16.7	24.2	VF	7.6.11.2
9596	2007 Nov 04, 04:11	111.9	03 32 29.95	-27 48 18.5	19.8	VF	7.6.11.2

NOTES.—The focal-plane temperature was  $-110^{\circ}\text{C}$  during the first two observations and  $-120^{\circ}\text{C}$  during the others. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

<sup>a</sup> All observations were continuous. The data were filtered on good-time intervals, and one mild flare was removed in observation 1431-0. The short time intervals with bad satellite aspect are negligible and have not been removed. The total exposure time for the 23 observations is 1.911 Ms.

<sup>b</sup> The average aim point, weighted by exposure time, is  $\alpha_{\text{J2000.0}} = 03^{\text{h}}32^{\text{m}}28.80^{\text{s}}$ ,  $\delta_{\text{J2000.0}} = -27^{\circ}48'23.0''$ .

<sup>c</sup> Roll angle describes the orientation of the *Chandra* instruments on the sky. The angle is between  $0^{\circ}$  and  $360^{\circ}$ , and it increases to the west of north (opposite to the sense of traditional position angle).

<sup>d</sup> The observing mode: F = Faint mode and VF = Very Faint mode.

<sup>e</sup> The version of the CXC pipeline software used for basic processing of the data.

observations. The allocated observations were successfully executed in 2007 September–November, raising the CDF-S exposure to  $\approx 2$  Ms and improving its sensitivity to be comparable to that of the CDF-N (e.g., Alexander et al. 2003, hereafter A03). Additional sky coverage at such flux levels is critically important as it substantially improves the statistical sample sizes of the faintest X-ray sources and also allows a basic assessment of the effects of cosmic variance. Furthermore, approximately doubling the exposure on previously detected sources substantially improves the constraints on their positions and spectral and variability properties.

In this paper, we present up-to-date *Chandra* source catalogs and data products derived from the full  $\approx 2$  Ms CDF-S data set along with details of the observations, data processing, and technical analysis. Detailed subsequent investigations and scientific interpretation of the new CDF-S sources will be presented in future papers, e.g., studies of heavily obscured and Compton-thick active galactic nuclei (AGNs), high-redshift AGNs, AGN spectra and variability, starburst and normal galaxies, and clusters and groups of galaxies. In § 2 we describe the observations and data reduction, and in § 3 we present the main and supplementary point-source catalogs and describe the methods used to create these catalogs. In § 4 we estimate the background and sensitivity across the survey region. We also present basic number-count results for point sources in § 5. We summarize in § 6.

The Galactic column density along the line of sight to the CDF-S is remarkably low:  $N_{\text{H}} = 8.8 \times 10^{19} \text{ cm}^{-2}$  (e.g., Stark

et al. 1992). The coordinates throughout this paper are J2000. An  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$ , and  $\Omega_{\Lambda} = 0.7$  cosmology is adopted.

## 2. OBSERVATIONS AND DATA REDUCTION

### 2.1. Observations and Observing Conditions

The CDF-S consists of 23 separate observations described in Table 1. The  $\approx 1$  Ms catalogs for the first 11 observations taken between 1999 October 14 and 2000 December 23 were presented in G02 and A03. Note that observation 581 (1999 October 14) was excluded from the data reduction and is not listed in Table 1 due to telemetry saturation and other problems. The second  $\approx 1$  Ms exposure consisted of 12 observations taken between 2007 September 20 and 2007 November 4.

The Advanced CCD Imaging Spectrometer imaging array (ACIS-I; Garmire et al. 2003) was used for all of the *Chandra* observations. The ACIS-I is composed of four  $1024 \times 1024$  pixel CCDs (CCDs I0–I3), covering a field of view of  $16.9' \times 16.9'$  ( $\approx 285 \text{ arcmin}^2$ ), and the pixel size of the CCDs is  $\approx 0.492''$ . The focal-plane temperature was  $-110^{\circ}\text{C}$  for observations 1431-0 and 1431-1 and  $-120^{\circ}\text{C}$  for the others. The 12 new observations were taken in Very Faint mode to improve the screening of background events and thus increase the sensitivity of ACIS in detecting faint X-ray sources (Vikhlinin 2001).

The background light curves for all 23 observations were inspected using EVENT BROWSER in the Tools for ACIS Real-time

Analysis (TARA; Broos et al. 2000) software package. Aside from a mild flare during observation 1431-0 (factor of  $\approx 3$  increase for  $\approx 5$  ks), all data sets are free from significant flaring, and the background is stable within  $\approx 20\%$  of typical quiescent *Chandra* values. After filtering on good-time intervals and removing the one mild flare, we are left with 1.911 Ms of total exposure time for the 23 observations.

Because of the differences in pointings and roll angles for the individual exposures, the total region covered by the entire CDF-S is 435.6 arcmin<sup>2</sup>, considerably larger than the ACIS-I field of view. Combining the 23 observations, the average aim point (weighted by exposure time) is  $\alpha_{J2000.0} = 03^{\text{h}}32^{\text{m}}28.80^{\text{s}}$ ,  $\delta_{J2000.0} = -27^{\circ}48'23.0''$ .

## 2.2. Data Reduction

The basic archive data products were processed with the *Chandra* X-ray Center (CXC) pipeline software versions listed in Table 1. The reduction and analysis of the data used *Chandra* Interactive Analysis of Observations (CIAO) tools whenever possible;<sup>16</sup> however, custom software, including the TARA package, was also used. Each observation was reprocessed using the CIAO tool `acis_process_events`, to correct for the radiation damage sustained by the CCDs during the first few months of *Chandra* operations using a charge transfer inefficiency (CTI) correction procedure (Townsend et al. 2000, 2002),<sup>17</sup> to remove the standard pixel randomization that blurs the *Chandra* point-spread function (PSF), and to apply a modified bad-pixel file as detailed below.

One important deviation from the standard *Chandra* reduction procedure outlined by the CXC is implementation of a stripped-down bad-pixel file. We note that the standard bad-pixel file supplied with all *Chandra* data currently excludes  $\approx 6\%$ – $7\%$  of the total effective area on front-illuminated devices (e.g., ACIS-I). A large fraction of the bad-pixel locations identified in this file, however, appear to be flagged solely because they show a few extra events (per Ms) almost exclusively below 0.5–0.7 keV.<sup>18</sup> Good events with energies above 0.7 keV that fall on these bad pixels are likely to be perfectly acceptable for source searching, as well as for photometry and spectral analysis, albeit with a few mild caveats regarding misinterpretation. Rather than reject all events falling on such columns, we instead adopted a procedure to only exclude events below a row-dependent energy of 0.5–0.7 keV.<sup>19</sup> To this end, we generated a stripped-down bad-pixel file, only selecting obvious bad columns and pixels above 1 keV; this excluded  $\approx 1.5\%$  of the total effective area on front-illuminated devices. Once the entire  $\approx 2$  Ms data set was combined, we isolated “hot” soft columns as those where the total number of events with energies below 0.7 keV was  $5\sigma$  or more above the mean. We then rejected any events in those columns that fell below a row-dependent energy of 0.5–0.7 keV; this removed 1% of all events.

Through inspection of the data in CCD coordinates, we additionally discovered that the CXC-preferred CIAO tool `acis_run_hotpix` failed to flag a substantial number of obvious

cosmic-ray afterglows ( $\sim 100$ – $200$  per observation, depending on exposure length), elevating the overall background and, in egregious cases, leaving afterglows to be mistaken as real sources. This problem appeared to be worse for Faint-mode data, presumably because the additional  $5 \times 5$  screening applied in Very Faint mode rejects the strongest afterglows (Vikhlinin 2001). To remedy this situation, we reverted to using the more stringent `acis_detect_afterglow` algorithm on all of our data. Notably, none of our sources has a count rate high enough that `acis_detect_afterglow` would reject true source counts, which we verified by inspection of events flagged by this routine. Even `acis_detect_afterglow` failed to reject all afterglows, and thus we created custom software to remove many remaining faint afterglows from the data. Working in CCD coordinates, we removed additional faint afterglows with 3 or more total counts occurring within 20 s (or equivalently six consecutive frames). In total, we removed 229 total events associated with afterglows. In all cases, we inspected the data set and found that such flagged events were isolated and not associated with apparent legitimate X-ray sources.

## 3. PRODUCTION OF THE POINT-SOURCE CATALOGS

The production of the point-source catalogs largely followed the procedure described in § 3 of A03. The main differences in the catalog-production procedure used here are the following:

1. Our main *Chandra* catalog includes sources detected by running `wavdetect` (Freeman et al. 2002) at a false-positive probability threshold of  $10^{-6}$ , less conservative than the  $10^{-7}$  value adopted by A03. Even with this revised threshold, we expect the fraction of false sources to be small; see § 3.2 for details.
2. Additional sensitivity can be obtained by merging the  $\approx 250$  ks Extended *Chandra* Deep Field–South (E-CDF-S; Lehmer et al. 2005, hereafter L05) with the  $\approx 2$  Ms CDF-S. An additional 86 X-ray sources were detected with this approach. These sources are presented in a supplementary catalog described in § 3.3.2.

### 3.1. Image and Exposure Map Creation

We registered the observations in the following manner. The `wavdetect` tool was run on each individual cleaned image to generate an initial source list. Centroid positions for each detected source were determined using the reduction tool `acis_extract` (AE; Broos et al. 2000).<sup>20</sup> The observations were registered to a common astrometric frame by matching X-ray centroid positions to optical sources detected in deep *R*-band images taken with the Wide Field Imager (WFI) of the Max Planck Gesellschaft/European Southern Observatory (ESO) telescope at La Silla (see § 2 of Giavalisco et al. 2004). The matching was performed using the CIAO tools `reproject_aspect` and `wcs_update` adopting a  $3''$  matching radius and a residual rejection limit<sup>21</sup> of  $0.6''$ ; 50–100 sources were typically used in each observation for the final astrometric solution. The tool `wcs_update` applied linear translations ranging from  $0.05''$  to  $0.34''$ , rotations ranging from  $-0.239^\circ$  to  $0.009^\circ$ , and scale stretches ranging from 0.999563 to 1.000714; individual registrations are accurate to  $\approx 0.3''$ . All of the observations were then reprojected to the frame of observation 2406, since this data set required the smallest translation to align it with the optical astrometric frame.

<sup>20</sup> The `acis_extract` software can be accessed from [http://www.astro.psu.edu/xray/docs/TARA/ae\\_users\\_guide.html](http://www.astro.psu.edu/xray/docs/TARA/ae_users_guide.html).

<sup>21</sup> This is a parameter used in `wcs_update` to remove source pairs based on pair positional offsets.

<sup>16</sup> See <http://cxc.harvard.edu/ciao/> for details on CIAO.

<sup>17</sup> Note that the CXC CTI correction procedure is only available for  $-120^\circ\text{C}$  data; thus, we did not CTI-correct observations 1431-0 and 1431-1.

<sup>18</sup> See [http://cxc.harvard.edu/cal/Acis/Cal\\_prods/badpix/](http://cxc.harvard.edu/cal/Acis/Cal_prods/badpix/).

<sup>19</sup> The energy range of 0.5–0.7 keV and frequency of occurrence were verified by visual inspection of such columns in our  $\approx 2$  Ms data set. We found that such “hot” soft columns were not clearly seen in any individual observations. The upper energy bound appears to vary as a function of distance from the readout edge of the front-illuminated CCDs, such that rows closest to the readout edge only have extra events below  $\approx 0.5$  keV, while those furthest away have extra events extending up to  $\approx 0.7$  keV.

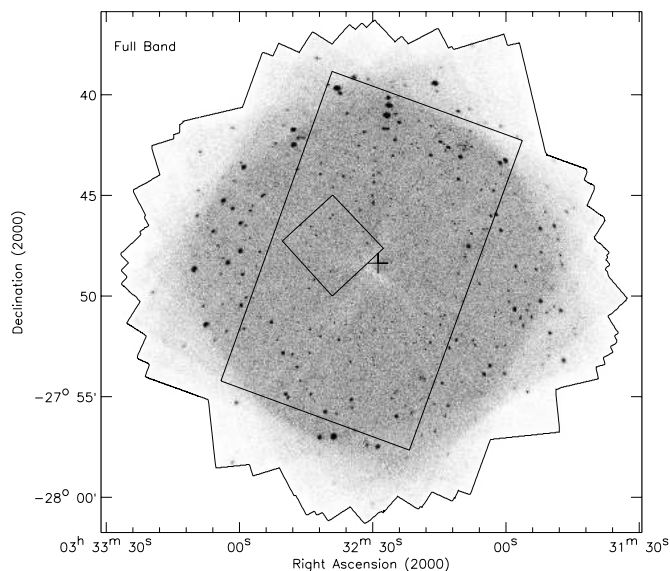


FIG. 1.—Full-band (0.5–8.0 keV) raw image of the  $\approx 2$  Ms CDF-S. The gray scales are linear. The apparent scarcity of sources near the field center is largely due to the small PSF at that location (see Figs. 4 and 10 for clarification). The black outline surrounding the image indicates the extent of all the CDF-S observations. The large rectangle indicates the GOODS-S (Giavalisco et al. 2004) region, and the central square indicates the *Hubble* Ultra Deep Field (UDF; Beckwith et al. 2006) region. The plus sign near the center of the images indicates the average aim point, weighted by exposure time (see Table 1).

We constructed images using the standard *ASCA* grade set (*ASCA* grades 0, 2, 3, 4, and 6) for three standard bands: 0.5–8.0 keV (full band; FB), 0.5–2.0 keV (soft band; SB), and 2–8 keV (hard band; HB). Figure 1 shows the full-band raw image. Exposure maps in the three standard bands were created following the basic procedure outlined in § 3.2 of Hornschemeier et al. (2001) and were normalized to the effective exposures of a source located at the average aim point. Briefly, this procedure takes into account the effects of vignetting, gaps between the CCDs, bad-column filtering, bad-pixel filtering, and the spatially dependent degradation in quantum efficiency due to contamination on the ACIS optical-blocking filters. A photon index of  $\Gamma = 1.4$  was assumed in creating the exposure maps, which is approximately the slope of the X-ray background in the 0.5–8.0 keV band (e.g., Marshall et al. 1980; Gendreau et al. 1995; Hasinger et al. 1998). We show the full-band exposure map in Figure 2. Using the full-band exposure map, we calculated the survey solid angle as a function of the minimum full-band effective exposure; the result is plotted in Figure 3. Approximately 56% and 42% of the CDF-S field has a full-band effective exposure greater than 1 Ms and 1.5 Ms, respectively, with a maximum effective exposure of  $\approx 1.884$  Ms (note this is slightly smaller than the 1.911 Ms total exposure since the aim points of all the *Chandra* observations were not exactly the same). The survey solid angles are comparable to those of the  $\approx 2$  Ms CDF-N (A03; Fig. 3, *dashed curve*).

Adaptively smoothed images were created using the CIAO tool `csmooth` on the raw images. Exposure-corrected smoothed images were then constructed following § 3.3 of Baganoff et al. (2003). We show in Figure 4 a color composite of the exposure-corrected smoothed images in the 0.5–2.0 keV (*red*), 2–4 keV (*green*), and 4–8 keV (*blue*) bands. Source searching was performed using only the raw images, while many of the detected X-ray sources are shown more clearly in the adaptively smoothed images.

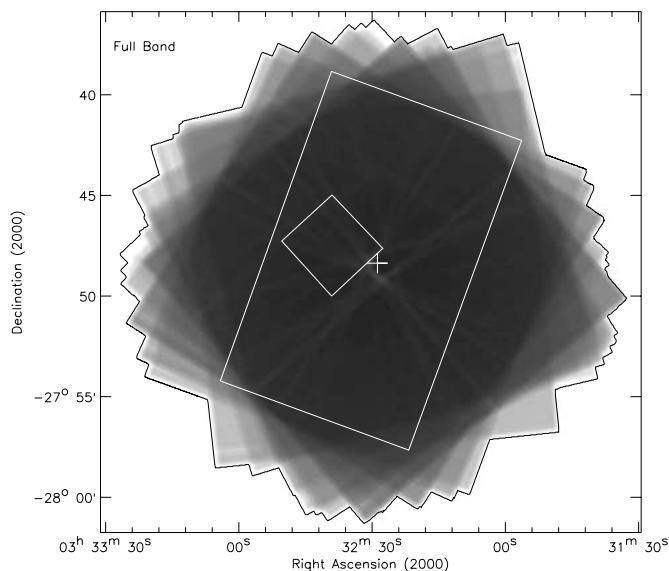


FIG. 2.—Full-band (0.5–8.0 keV) exposure map of the  $\approx 2$  Ms CDF-S. The darkest areas represent the highest effective exposure times (the maximum value is 1.884 Ms). The gray scales are logarithmic. The regions and the plus sign have the same meaning as those in Fig. 1.

### 3.2. Point-Source Detection

Point-source detection was performed in each of the three standard bands with `wavdetect` using a “ $\sqrt{2}$  sequence” of wavelet scales (i.e., 1,  $\sqrt{2}$ , 2,  $2\sqrt{2}$ , 4,  $4\sqrt{2}$ , 8,  $8\sqrt{2}$ , and 16 pixels). The criterion for source detection is that a source must be found with a given false-positive probability threshold in at least one of the three standard bands. For the main *Chandra* source catalog discussed in § 3.3.1, the false-positive probability threshold in each band was set to  $1 \times 10^{-6}$ .

If we conservatively consider the three images searched to be independent,  $\approx 18$  false detections are expected in the main *Chandra* source catalog for the case of a uniform background. However, this false-source estimate is conservative, since a single pixel usually should not be considered a source-detection cell, particularly at large off-axis angles (`wavdetect` suppresses

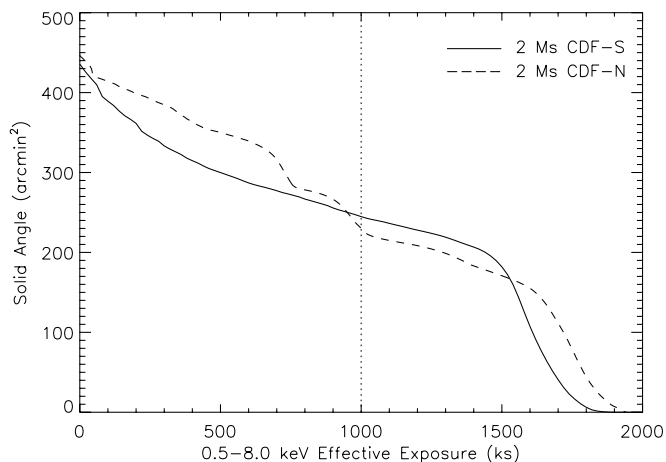


FIG. 3.—Amount of survey solid angle having at least a given amount of full-band effective exposure for the  $\approx 2$  Ms CDF-S (*solid curve*). The maximum exposure is  $\approx 1.884$  Ms. The vertical dotted line shows an effective exposure of 1 Ms. About 245 arcmin<sup>2</sup> ( $\approx 56\%$ ) of the CDF-S survey area has  $>1$  Ms effective exposure. Corresponding data from the  $\approx 2$  Ms CDF-N (A03) are plotted as a dashed curve for comparison.

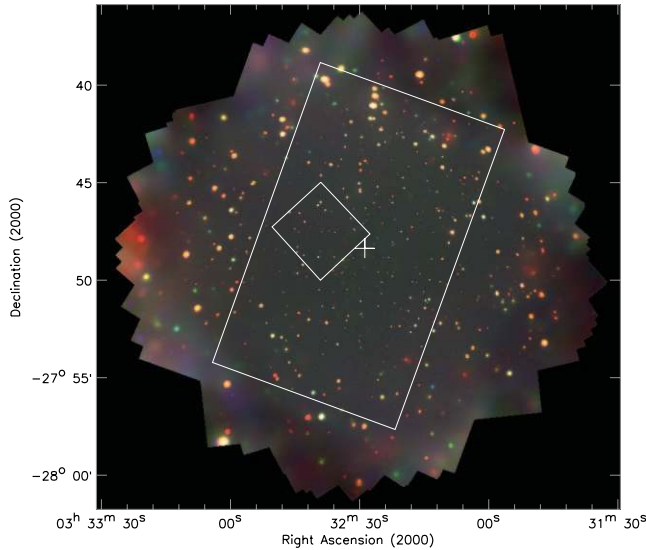


FIG. 4.—*Chandra* “false-color” image of the  $\approx 2$  Ms CDF-S. This image is a color composite of the exposure-corrected adaptively smoothed images in the 0.5–2.0 keV (red), 2–4 keV (green), and 4–8 keV (blue) bands. The apparent smaller size and lower brightness of sources near the field center is due to the small PSF at that location. The regions and the plus sign have the same meaning as those in Fig. 1.

fluctuations on scales smaller than the PSF). As quantified in § 3.4.1 of A03, the number of false-sources is likely  $\approx 2$ –3 times less than our conservative estimate. We also provide additional source-significance information by running *wavdetect* using false-positive probability thresholds of  $1 \times 10^{-7}$  and  $1 \times 10^{-8}$ . These results are presented in § 3.3.1, which can be used to perform more conservative source screening if desired.

### 3.3. Point-Source Catalogs

#### 3.3.1. Main *Chandra* Source Catalog

The source lists resulting from the *wavdetect* runs discussed in § 3.2 with false-positive probability threshold of  $1 \times 10^{-6}$  were merged to create the main point-source catalog presented in Table 2, which consists of 462 point sources. Whenever possible, we have quoted the position determined in the full band; when a source is not detected in the full band, we used, in order of priority, the soft-band position or hard-band position. For cross-band matching, we used a matching radius of  $2.5''$  for sources within  $6'$  of the average aim point and  $4.0''$  for larger off-axis angles. These matching radii were chosen by inspecting histograms showing the number of matches obtained as a function of

angular separation (e.g., see § 2 of Boller et al. 1998); the mismatch probability is  $\lesssim 1\%$  over the entire field. A few mismatches near the edge of the field were removed through visual inspections.

We improved the *wavdetect* source positions using the centroid and matched-filter positions generated with AE. The centroid is simply the mean position of all events within the AE extraction region, while the matched-filter position is the position found by correlating the full-band image in the vicinity of each source with a combined PSF. The combined PSF is produced by combining the “library” PSF of a source for each observation, weighted by the number of detected counts.<sup>22</sup> This technique takes into account the fact that, due to the complex PSF at large off-axis angles, the X-ray source position is not always located at the peak of the X-ray emission. The *wavdetect*, centroid, and matched-filter techniques provide comparable accuracy on axis, while the matched-filter technique performs better off axis. We chose the matched-filter positions as our default and then visually inspected each source. When the adopted position appeared to deviate from the apparent center of the source by more than  $0.1''$ , we modified the position manually such that it was visually consistent with the apparent center.

We refined the absolute X-ray source positions by matching the X-ray sources in the main *Chandra* catalog to the WFI *R*-band optical sources (see § 3.1). There are  $\approx 30,000$  optical sources across the CDF-S field, which have accurate positions with positional error  $\Delta_o \approx 0.1''$ .<sup>23</sup> We selected relatively bright optical sources with AB magnitudes  $R \leq 24$  ( $\approx 5,500$  sources) and matched them to the X-ray sources using a  $2.5''$  matching radius. There are eight cases where one X-ray source has two optical counterparts. The *R*-band magnitudes of the two counterparts differ by less than 1 in all cases, and thus we selected the closer one as the most probable counterpart. We also visually inspected the optical counterparts and, for purposes of positional checking, only keep those sources that are pointlike or slightly extended; 10 extended sources were removed. Under these criteria, 229 X-ray sources have bright optical counterparts. We estimated the expected number of false matches by manually shifting the X-ray source coordinates in right ascension and declination by  $5.0''$  (both positive and negative shifts) and re-correlating with the optical sources. On average, the number of false matches is  $\approx 35$  ( $\approx 15\%$ ), and the median offset of these false matches is  $\approx 1.71''$ . By comparing the X-ray and optical source positions, we found small shift and plate-scale corrections. These corrections have been applied

<sup>22</sup> The PSFs are taken from the CXC PSF library; see <http://cxc.harvard.edu/ciao/dictionary/psflib.html>.

<sup>23</sup> See [http://archive.stsci.edu/pub/hlsp/goods/v1/h\\_goods\\_v1.0\\_rdm.html](http://archive.stsci.edu/pub/hlsp/goods/v1/h_goods_v1.0_rdm.html).

TABLE 2  
MAIN *Chandra* CATALOG

No. (1)	X-RAY COORDINATES				COUNTS						
	$\alpha_{2000}$ (2)	$\delta_{2000}$ (3)	POS ERR (4)	OFF-AXIS (5)	FB (6)	FB Upp Err (7)	FB Low Err (8)	SB (9)	SB Upp Err (10)	SB Low Err (11)	
1.....	03 31 34.19	−27 50 04.2	1.6	12.19	26.1	11.1	11.8	13.5	−1.0	−1.0	
2.....	03 31 35.79	−27 51 34.7	1.9	12.14	14.9	−1.0	−1.0	12.1	7.3	7.2	
3.....	03 31 40.15	−27 47 46.3	1.3	10.77	33.6	11.8	11.8	25.8	8.4	8.1	
4.....	03 31 40.93	−27 46 21.8	1.1	10.77	61.2	14.0	14.0	16.0	−1.0	−1.0	
5.....	03 31 44.23	−27 49 25.5	1.0	9.91	79.5	19.4	19.4	37.8	12.5	12.5	

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 2 is presented in its entirety in the electronic edition of the *Astrophysical Journal Supplement*. A portion is shown here for guidance regarding its form and content. The full table contains 49 columns of information on the 462 X-ray sources.

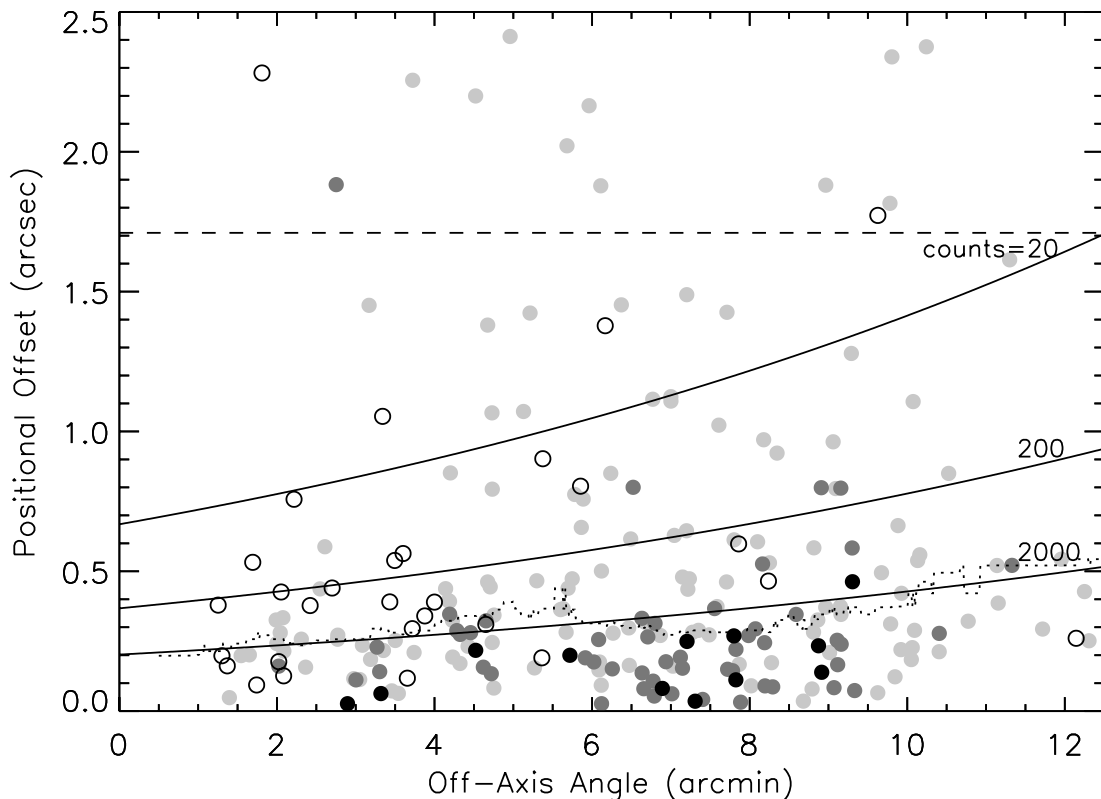


FIG. 5.—Positional offset vs. off-axis angle for sources in the main *Chandra* catalog that were matched to WFI *R*-band optical sources with AB magnitude  $R \leq 24$  to within  $2.5''$ . Black, dark gray, light gray, and open circles represent *Chandra* sources with  $\geq 2000$ ,  $\geq 200$ ,  $\geq 20$ , and  $< 20$  counts in the energy band where the source position was determined, respectively. The dotted curve shows the running median of all sources in bins of  $2'$ . The median offset of the expected false matches ( $\approx 1.71''$ ) is indicated by the dashed line. These data were used to derive the  $\approx 85\%$  confidence-level positional uncertainties of the X-ray sources in the main catalog; see eq. (1). Three solid curves indicate the  $\approx 85\%$  confidence-level positional uncertainties for sources with counts of 20, 200, and 2000. The numbers of black, dark gray, and light gray circles lying below/above their corresponding solid curves are 11/1, 48/4, and 116/20, respectively. Note that sources with more than 20 or 200 counts will have expected positional uncertainties smaller than those indicated by the corresponding solid curves.

to the positions of all the X-ray sources in the main and supplementary catalogs, resulting in small ( $< 0.2''$ ) astrometric shifts.

We investigated the accuracy of the X-ray source positions using these 229 X-ray-detected bright optical sources. Figure 5 shows the positional offset between the X-ray sources and their optical counterparts as a function of the off-axis angle. The median offset is  $\approx 0.36''$ . However, there are clear off-axis-angle and source-count dependencies. The off-axis-angle dependence is due to the degradation of the *Chandra* PSF at large off-axis angles, while the count dependence is due to the difficulty of finding the centroid of a faint X-ray source. Simulations have shown that the offsets of *wavdetect* positions appear to increase exponentially with off-axis angle and decrease with the number of source counts in a power-law form (e.g., Kim et al. 2007). Based on Figure 5 and taking into account the probability of false matches, we derived an empirical relation for the positional uncertainties of the X-ray sources in our sample, which is

$$\log \Delta_X = 0.0326\theta - 0.2595 \log C + 0.1625, \quad (1)$$

where  $\Delta_X$  is the positional uncertainty in arcseconds,  $\theta$  the off-axis angle in arcminutes, and  $C$  the source counts in the energy band where the source position was determined. We set an upper limit of 2000 on  $C$  as the positional accuracy does not improve significantly beyond that level. Positional uncertainties for  $C = 20$ , 200, and 2000 are shown in Figure 5. The stated positional uncertainties are for the  $\approx 85\%$  confidence level and are smaller than the *wavdetect* positional errors, especially at large off-axis

angles, because of our positional refinement described above. A few sources in Figure 5 have unexpectedly large positional offsets; they could be false matches.<sup>24</sup> There is also the possibility that a few of them are off-nuclear X-ray sources (e.g., Hornschemeier et al. 2004; Lehmer et al. 2006). Figure 6 shows the distributions of the positional offsets in four bins of different X-ray positional uncertainties, as well as the expected numbers of false matches assuming a uniform spatial distribution of the  $R \leq 24$  optical sources. These histograms illustrate clearly the reliability of our positional error estimates calculated using equation (1).

The main *Chandra* X-ray source catalog is presented in Table 2, with the details of the columns given below.

1. Column (1): the source number. Sources are listed in order of increasing right ascension.
2. Columns (2) and (3): the right ascension and declination of the X-ray source, respectively. These positions have been determined following the procedure described above. To avoid truncation error, we quote the positions to higher precision than in the International Astronomical Union (IAU)-registered names beginning with the acronym “CXO CDFS.”
3. Column (4): the  $\approx 85\%$  confidence-level positional uncertainty in arcseconds. As shown above, the positional uncertainty depends on off-axis angle and the number of detected counts and

<sup>24</sup> For example, the source with  $> 200$  counts and a positional offset of  $\approx 1.9''$  in Fig. 5 is source 289 in the main *Chandra* catalog (see Table 2). This source does not have any optical counterpart after adopting a more appropriate matching radius, as shown in the catalog.

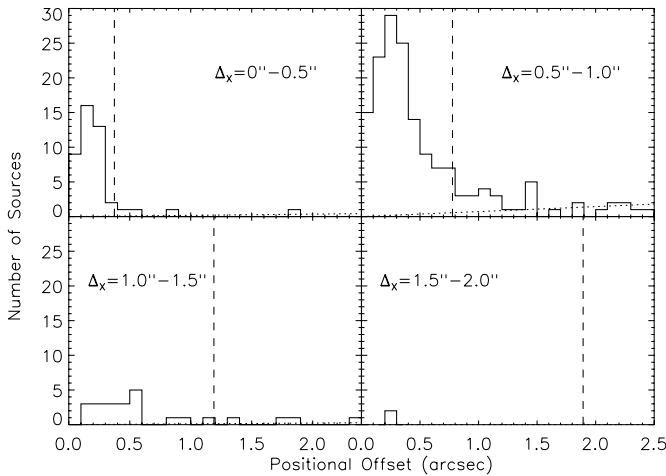


FIG. 6.—Histograms showing the distributions of positional offset for sources in the main *Chandra* catalog that were matched to WFI *R*-band optical sources with  $R \leq 24$  within  $2.5''$ . X-ray sources were divided into four bins based on their positional uncertainties estimated using eq. (1):  $0''\text{--}0.5''$ ,  $0.5''\text{--}1.0''$ ,  $1.0''\text{--}1.5''$ , and  $1.5''\text{--}2.0''$ . The vertical dashed line indicates the median positional uncertainty for X-ray sources in each bin. Dotted lines show how many random  $R \leq 24$  optical sources are expected as a function of the positional offset. Less than 20% of the optical counterparts lie beyond the median X-ray positional uncertainties in all cases.

is estimated following equation (1). The minimum positional uncertainty is  $\approx 0.23''$  for sources in the main catalog, and the maximum value is  $\approx 1.90''$ .

4. Column (5): the off-axis angle of the X-ray source in arcminutes. This is calculated using the source position given in columns (2) and (3) and the average aim point of the CDF-S (see Table 1).

5. Columns (6)–(14): the source counts and the corresponding  $1\sigma$  statistical errors (Gehrels 1986) or the upper limits on source counts for the three standard bands, respectively. The entries have not been corrected for vignetting. Source counts and statistical errors have been calculated using circular-aperture photometry; extensive testing has shown that this method is more reliable than the *wavdetect* photometry (e.g., Brandt et al. 2001; A03). The circular aperture was centered at the position given in columns (2) and (3) for all bands. We have also computed photometry using AE, and the results are in good agreement with this circular-aperture photometry.

The local background is determined in an annulus outside of the source-extraction region. The mean number of background counts per pixel is calculated from a Poisson model using  $n_1/n_0$ , where  $n_0$  is the number of pixels with 0 counts and  $n_1$  is the number of pixels with 1 count (e.g., A03). By ignoring all pixels with more than 1 count, this technique is robust against background contamination from sources. The principal requirement for using this Poisson-model technique is that the background counts are low and follow a Poisson distribution; we show in § 4 that the background of the  $\approx 2$  Ms exposure meets this criterion. We note that the background estimation is problematic for several sources that are located close to bright sources or near the edge of the survey field where there is a strong gradient in exposure time. For each of these sources, we have measured its background counts in the background maps described in § 4, using an annulus outside of the source-extraction region. Note that when constructing the background maps, we filled in the masked regions with a local background assuming a probability distribution; thus, small additional uncertainties could be introduced during this process and are carried on to the background estimation here. There are

17 such sources, and they are marked with “B” in column (49) of Table 2. The net number of source counts is calculated by subtracting the background counts from the source counts.

For sources with fewer than 1000 full-band counts, we have chosen the aperture radii based on the encircled-energy function of the *Chandra* PSF as determined using the CXC’s MKPSF software (Feigelson et al. 2000; Jerius et al. 2000). In the soft band, where the background is lowest, the aperture radius was set to the 95% encircled-energy radius of the PSF. In the full and hard bands, the 90% encircled-energy radius of the PSF was used. Appropriate aperture corrections were applied to the source counts by dividing the extracted source counts by the encircled-energy fraction for which the counts were extracted.

For sources with more than 1000 full-band counts, systematic errors in the aperture corrections often exceed the expected errors from photon statistics when the apertures described in the previous paragraph are used. Therefore, for such sources we used larger apertures to minimize the importance of the aperture corrections; this is appropriate since these bright sources dominate over the background. We set the aperture radii to be twice the 90% encircled-energy full-band radii and inspected these sources to verify that the measurements were not contaminated by neighboring objects. No aperture corrections were applied to these sources.

Manual correction of the source photometry was performed for sources having overlapping PSFs. We manually separated 18 close doubles and four close triples, and these sources are flagged with “S” in column (49) of Table 2.

We have performed several consistency tests to verify the quality of the photometry. For example, we have checked that the sum of the counts measured in the soft and hard bands does not differ from the counts measured in the full band by an amount larger than that expected from measurement error. Systematic errors that arise from differing full-band counts and soft-band plus hard-band counts are estimated to be  $\leq 4\%$ .

When a source is not detected in a given band, an upper limit is calculated; upper limits are indicated as a  $-1.00$  in the error columns. All upper limits are determined using the circular apertures described above. When the number of counts in the aperture is  $\leq 10$ , the upper limit is calculated using the Bayesian method of Kraft et al. (1991) for 99% confidence. The uniform prior used by these authors results in fairly conservative upper limits (see Bickel 1992), and other reasonable choices of priors do not materially change our scientific results. For larger numbers of counts in the aperture, upper limits are calculated at the  $3\sigma$  level for Gaussian statistics.

6. Columns (15) and (16): the right ascension and declination of the optical counterpart, which were obtained by matching the X-ray source positions (cols. [2] and [3]) to WFI *R*-band source positions using a matching radius that is 1.5 times the quadratic sum of the positional errors of the X-ray and optical sources [i.e.,  $r_m = 1.5(\Delta_x^2 + \Delta_o^2)^{1/2}$ ]. This matching radius was chosen to provide a large number of optical counterparts without introducing too many false matches. The WFI *R*-band observations have a  $5\sigma$  limiting AB magnitude of 27.3 over the entire CDF-S field. For four sources (our sources 74, 283, 328, and 431) that have more than one optical match, the magnitude difference between the counterparts is less than 3 in all cases, and therefore the source with the smallest offset was selected as the most probable counterpart. Using these criteria, 344 ( $\approx 74\%$ ) of the sources have optical counterparts. Sources with no optical counterparts have these right ascension and declination values set to “00 00 00.00” and “–00 00 00.0.” We tested the reliability of the matching by shifting the X-ray source coordinates and



re-correlating with the optical sources. The matching is reliable (false-match probability  $\lesssim 8\%$ ) to  $R \approx 24$ . The false-match probability rises to  $\approx 18\%$ ,  $\approx 27\%$ , and  $\approx 35\%$  at  $R \approx 25$ , 26, and 27, respectively.

7. Column (17): the measured offset between the optical and X-ray sources in arcseconds. Sources with no optical counterparts have a value set to  $-1.00$ . The offsets for all matches are below  $2.0''$ .

8. Column (18): the  $R$ -band AB magnitude of the optical counterpart. Sources with no optical counterparts have a value set to  $-1.00$ .

9. Columns (19) and (20): the corresponding source number and  $i$ -band AB magnitude from the Great Observatories Origins Deep Survey–South (GOODS-S) version 2.0  $i$ -band source catalog.<sup>25</sup> We matched the positions of the optical counterparts (see cols. [15] and [16]) to the GOODS-S source positions using a matching radius of  $0.5''$ . In 6 cases (our sources 88, 120, 135, 155, 313, and 322) where there is more than one GOODS-S source matching to an optical counterpart, we selected the GOODS-S source with the smallest offset as the most probable match. For the 344 optical counterparts, 218 matches were found; note that the GOOD-S field does not cover the whole CDF-S. By shifting the coordinates of the optical counterparts and re-correlating with the GOODS-S sources, we estimated the false-match probability to be  $\lesssim 5\%$ . The GOODS-S  $i$ -band observations have a  $5\sigma$  limiting AB magnitude of 28.5. The  $i$ -band magnitude is the SExtractor (Bertin & Arnouts 1996) corrected isophotal magnitude. Sources with no GOODS-S match have these two columns set to  $-1$  and  $-1.00$ , respectively.

10. Columns (21) and (22): the corresponding coordinate-based source name and  $z$ -band AB magnitude from the Galaxy Evolution from Morphologies and SEDs (GEMS) source catalog (Caldwell et al. 2008). We matched the positions of the optical counterparts (see cols. [15] and [16]) to the GEMS source positions using a matching radius of  $0.5''$ . In one case (our source 74) where there is more than one GEMS source matching to an optical counterpart, we selected the GEMS source with the smallest offset as the most probable match. For the 344 optical counterparts, 297 matches were found. By shifting the coordinates of the optical counterparts and re-correlating with the GEMS sources, we estimated the false-match probability to be  $\lesssim 2\%$ . The GEMS  $z$ -band observations have a  $5\sigma$  limiting AB magnitude of 27.3 over the entire CDF-S field. The  $z$ -band magnitude is the SExtractor MAG-BEST magnitude. Sources with no GEMS match have these two columns set to  $-1$  and  $-1.00$ , respectively.

11. Columns (23) and (24): the corresponding source number and  $K_s$ -band AB magnitude from the source catalog for the ESO/New Technology Telescope SOFI survey of the CDF-S region.<sup>26</sup> We matched the positions of the optical counterparts (see cols. [15] and [16]) to the SOFI source positions using a matching radius of  $0.75''$ . For the 344 optical counterparts, 266 matches were found. By shifting the coordinates of the optical counterparts and re-correlating with the SOFI sources, we estimated the false-match probability to be  $\lesssim 1\%$ . The SOFI  $K_s$ -band observations have a  $5\sigma$  limiting AB magnitude of 23.0 over the entire CDF-S field. The  $K_s$ -band magnitude is the SExtractor-corrected isophotal magnitude. Sources with no SOFI match have these two columns set to  $-1$  and  $-1.00$ , respectively.

12. Columns (25) and (26): the corresponding source number and IRAC  $5.8\mu\text{m}$  flux density ( $f_{58}$ ) from the *Spitzer* IRAC/

MUSYC Public Legacy Survey in the E-CDF-S (SIMPLE) source catalog.<sup>27</sup> We matched the positions of the optical counterparts (see cols. [15] and [16]) to the SIMPLE source positions using a matching radius of  $0.75''$ . For the 344 optical counterparts, 306 matches were found. By shifting the coordinates of the optical counterparts and re-correlating with the SIMPLE sources, we estimated the false-match probability to be  $\lesssim 2\%$ . The SIMPLE  $5.8\mu\text{m}$  observations have a  $5\sigma$  limiting AB magnitude of 21.9–22.5 over the entire CDF-S field; the limiting magnitude is spatially dependent for SIMPLE. The  $5.8\mu\text{m}$  flux density is the aperture flux density in a  $2.0''$  circular aperture, normalized to an AB magnitude zero point of 25. Note that an aperture correction of  $\approx 1.5$  was not applied to these fluxes; i.e., the aperture-corrected AB magnitude is  $m(\text{AB}) = 25 - 2.5 \log_{10}(1.5f_{58})$ . Sources with no SIMPLE match have these two columns set to  $-1$  and  $-1.00$ , respectively.

13. Columns (27) and (28): the corresponding spectroscopic redshift and the reference for the redshift. Secure spectroscopic redshifts were collected from Le Fèvre et al. (2004), Szokoly et al. (2004), Mignoli et al. (2005), Ravikumar et al. (2007), Popesso et al. (2008), and Vanzella et al. (2008) with the reference numbers of 1–6 in column (28), respectively. A matching radius of  $0.5''$  was used when matching the optical counterparts (see cols. [15] and [16]) to the redshift catalogs. Of the 344 optical counterparts 190 have redshift measurements. By shifting the coordinates of the optical counterparts and re-correlating with the redshift catalogs, we estimated the false-match probability to be  $\lesssim 1\%$ . Sources with no secure spectroscopic redshift have these two columns set to  $-1.000$  and  $-1$ , respectively. Note that there are also photometric redshifts available in the literature (e.g., Mobasher et al. 2004; Wolf et al. 2004), but these are not included in our catalogs.

14. Column (29): the corresponding  $\approx 1$  Ms CDF-S source number from the main *Chandra* catalog presented in A03 (see col. [1] of Table A2a in A03). We matched our X-ray source positions to A03 source positions using a matching radius that is the quadratic sum of the  $\approx 3\sigma$  positional errors of the CDF-S and A03 X-ray sources. The  $3\sigma$  positional error of a CDF-S source is approximately twice the positional error quoted in column (4) (i.e.,  $2\Delta_X$ ), and that of an A03 source is approximately twice the positional error quoted in Table A2a of A03. The false match probability is less than 1% with this matching radius. Only one A03 match was found for each matched source. In one case where two close-double sources matched to one A03 source, we chose the source with the smallest offset (source 433) as the most probable match. We manually set the counterpart of the source with source number 437 to be source 312 in A03, because A03 apparently underestimated the positional error of this source. Sources with no A03 match have a value of  $-1$ .

15. Columns (30) and (31): the right ascension and declination of the corresponding A03 source indicated in column (29). Sources with no A03 match have right ascension and declination values set to “00 00 00.00” and “–00 00 00.0”.

16. Columns (32) and (33): the corresponding  $\approx 1$  Ms CDF-S source “ID” number and “XID” number from the main *Chandra* catalog presented in G02 (see their Table 2). When matching our CDF-S source positions with G02 counterparts, we removed offsets to the G02 positions of  $-1.2''$  in right ascension and  $0.8''$  in declination (see § A3 of A03); these positions are corrected in the quoted source positions in columns (34) and (35). We used a matching radius that is the quadratic sum of the  $\approx 3\sigma$  positional errors of the CDF-S and G02 X-ray sources. The  $3\sigma$  positional

<sup>25</sup> See Giavalisco et al. (2004) and [http://archive.stsci.edu/pub/hlsp/goods/catalog\\_r2/](http://archive.stsci.edu/pub/hlsp/goods/catalog_r2/).

<sup>26</sup> See [http://www.eso.org/sci/activities/projects/eis/surveys/summary\\_DPS.html](http://www.eso.org/sci/activities/projects/eis/surveys/summary_DPS.html).

<sup>27</sup> See <http://ssc.spitzer.caltech.edu/legacy/simplehistory.html>.



TABLE 3  
SUMMARY OF *Chandra* SOURCE DETECTIONS

BAND (keV)	NUMBER OF SOURCES	DETECTED COUNTS PER SOURCE			
		Maximum	Minimum	Median	Mean
Full (0.5–8.0).....	403	21579.7	11.4	101.0	410.6
Soft (0.5–2.0).....	392	15929.7	4.7	53.0	269.9
Hard (2–8).....	265	5664.3	7.7	88.6	216.9

error of a CDF-S source is approximately twice the positional error quoted in column (4), and that of a G02 source is quoted in Table 2 of G02. Only one G02 match was found for each matched source. In three cases where two close-double sources matched to one G02 source, we chose the source with the smallest offset (sources 142, 195, and 275) as the most probable match. Sources with no G02 match have a value of  $-1$ .

17. Columns (34) and (35): the right ascension and declination of the corresponding G02 source indicated in columns (32) and (33). Note that the quoted positions have been corrected by the offsets described in columns (32) and (33) (see § A3 of A03). Sources with no G02 match have right ascension and declination values set to “00 00 00.00” and “–00 00 00.0.”

18. Columns (36)–(38): the effective exposure times determined from the standard-band exposure maps (see § 3.1 for details on the exposure maps). Dividing the counts listed in columns (6)–(14) by the corresponding effective exposures provides the vignetting-corrected and quantum-efficiency degradation corrected count rates.

19. Columns (39)–(41): the band ratio, defined as the ratio of counts between the hard and soft bands, and the corresponding upper and lower errors, respectively. Quoted band ratios have been corrected for differential vignetting between the hard band and soft band using the appropriate exposure maps. Errors for this quantity are calculated following the “numerical method” described in § 1.7.3 of Lyons (1991); this avoids the failure of the standard approximate variance formula when the number of counts is small (see § 2.4.5 of Eadie et al. 1971). Note that the error distribution is not Gaussian when the number of counts is small. Upper limits are calculated for sources detected in the soft band but not the hard band, and lower limits are calculated for sources detected in the hard band but not the soft band. For these sources, the upper and lower errors are set to the computed band ratio. Sources detected only in the full band have band ratios and corresponding errors set to  $-1.00$ .

20. Columns (42)–(44): the effective photon index ( $\Gamma$ ) with upper and lower errors, respectively, for a power-law model with the Galactic column density given in § 1. When the number of source counts is not low, the effective photon index has been calculated based on the band ratio in column (39) using the CXC’s Portable, Interactive, Multi-Mission Simulator (PIMMS). Upper limits are calculated for sources detected in the hard band but not the soft band, and lower limits are calculated for sources detected in the soft band but not the hard band. For sources with only limits on the effective photon index, the upper and lower errors are set to the computed effective photon index.

A source with a low number of counts is defined as being (1) detected in the soft band with  $<30$  counts and not detected in the hard band, (2) detected in the hard band with  $<15$  counts and not detected in the soft band, (3) detected in both the soft and hard bands, but with  $<15$  counts in each, or (4) detected only in the full band. When the number of counts is low, the photon index

is poorly constrained and is set to  $\Gamma = 1.4$ , a representative value for faint sources that should yield reasonable fluxes. In this case, the upper and lower errors are set to 0.00.

21. Columns (45)–(47): observed-frame fluxes in the three standard bands; quoted fluxes are in units of  $\text{ergs cm}^{-2} \text{s}^{-1}$ . Fluxes have been computed using the counts in columns (6)–(14), the appropriate exposure maps (cols. [36]–[38]), and the effective photon indices given in column (42). The fluxes have not been corrected for absorption by the Galaxy or material intrinsic to the source. For a power-law model with  $\Gamma = 1.4$ , the soft-band and hard-band Galactic absorption corrections are  $\approx 2.1\%$  and  $\approx 0.1\%$ , respectively. More accurate fluxes for these sources would require direct fitting of the X-ray spectra for each observation, which is model dependent and beyond the scope of this paper.

22. Column (48): the logarithm of the minimum false-positive probability run with *wavdetect* in which each source was detected (see § 3.2). A lower false-positive probability indicates a more significant source detection. Of our sources, 398 ( $\approx 86\%$ ) and 357 ( $\approx 77\%$ ) are detected with false-positive probability thresholds of  $1 \times 10^{-7}$  and  $1 \times 10^{-8}$ , respectively.

23. Column (49): notes on the sources. “E” refers to sources at the edge that lie partially outside of the survey area. “S” refers to close doubles or triples where manual separation was required. “B” refers to sources with background counts estimated using the background maps (see cols. [6]–[14] of Table 2).

In Table 3 we summarize the source detections in the three standard bands. In total 462 point sources are detected, 327 of which were present in the main *Chandra* catalogs for the  $\approx 1$  Ms CDF-S (G02 and A03), and thus 135 sources are new. For the 308 sources that were detected in the main catalog of A03, we find general agreement between the derived X-ray properties presented here and in A03. For example, we have compared the full-band count rates of these 308 sources between the two catalogs. The median ratio of the count rates is  $\approx 0.98$ , with an interquartile range of  $\approx 0.85$ – $0.12$ . Furthermore, the approximately doubled exposure improves the source positions and spectral constraints significantly, and thus the  $\approx 2$  Ms CDF-S catalogs presented here supersede those in A03.

Eighteen of the 326 sources detected in the main catalog of A03 are undetected here. Nine of these were detected in *wavdetect* runs with a false-positive probability threshold of  $1 \times 10^{-5}$  in the present analysis. The other nine sources were weakly detected in A03 with less than 17 full-band counts. We examined the regions of these nine sources in the three  $\approx 2$  Ms images and found no emission clearly distinct from the background. Ten of the eighteen sources have optical counterparts in the WFI R-band source catalog within  $1.3''$ , and three of them are present in the supplementary optically bright *Chandra* catalog (see § 3.3.3), suggesting that they are likely true X-ray sources. As the second  $\approx 1$  Ms exposure was taken  $\approx 7$  years later, these 18 sources could be below our detection limit due to source variability or background

TABLE 4  
SOURCES DETECTED IN ONE BAND BUT NOT ANOTHER

DETECTION BAND (keV)	NONDETECTION ENERGY BAND		
	Full	Soft	Hard
Full (0.5–8.0).....	...	67	141
Soft (0.5–2.0).....	56	...	166
Hard (2–8).....	3	39	...

NOTE.—For example, there were 67 sources detected in the full band that were not detected in the soft band.

fluctuations. A 30% median flux variability has been observed for sources in the first  $\approx 1$  Ms data set (Paolillo et al. 2004), which is expected to increase here owing to the long observation interval. There is also the possibility that some of the missing sources were false detections in A03, since approximately three to nine false detections were expected (A03).

Four of the 304 sources in the main catalog of G02 are not detected here, two of which were detected in *wavdetect* runs with a false-positive probability threshold of  $1 \times 10^{-5}$ . All four sources lie at large off-axis angles, and none of them is in the A03 main catalog. These sources could be below our detection limit due to source variability or background fluctuations. Note that 19 G02 sources that were not detected in A03 are detected here, suggesting that these are likely true sources. These sources were probably not reported in the A03 main catalog due to the conservative *wavdetect* false-positive probability threshold ( $1 \times 10^{-7}$ ) adopted in that work.

In Table 4 we summarize the number of sources detected in one band but not another. There are three sources detected only in the hard band. For comparison, there is one source in the  $\approx 1$  Ms CDF-S that was detected only in the hard band (A03). In Figure 7 we show the distributions of detected counts in the three standard bands. The median numbers of counts for the full band, soft band, and hard band are  $\approx 101$ ,  $\approx 53$  and  $\approx 89$ , respectively. There are 202 sources with  $>100$  full-band counts, for which basic spectral analyses are possible, and 33 sources with  $>1000$  full-band counts. In Figure 8 we show the distributions of X-ray flux in the

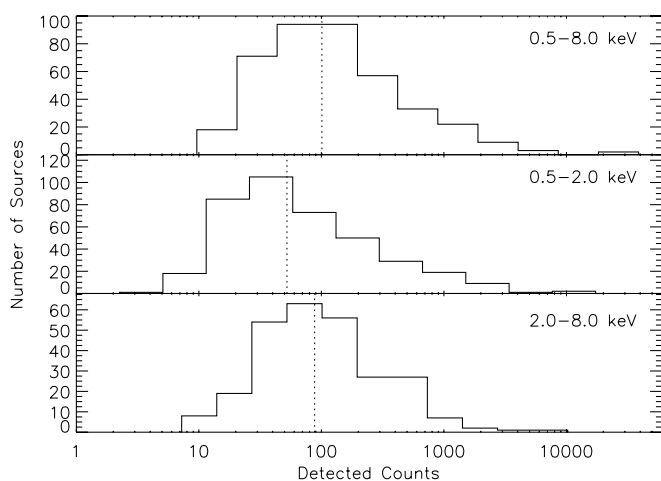


FIG. 7.—Histograms showing the distributions of detected source counts for sources in the main *Chandra* catalog in the full (top), soft (middle), and hard (bottom) bands. Sources with upper limits have not been included in these diagrams. The vertical dotted lines indicate the median numbers of counts in each band (see Table 3).

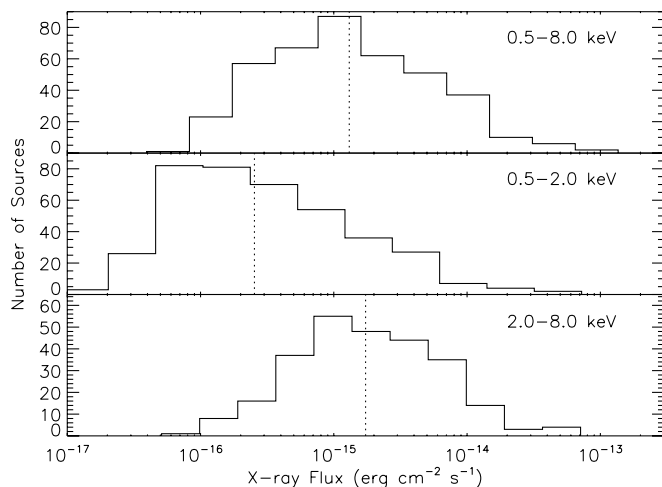


FIG. 8.—Histograms showing the distributions of X-ray fluxes for sources in the main *Chandra* catalog in the full (top), soft (middle), and hard (bottom) bands. Sources with upper limits have not been included in this figure. The vertical dotted lines indicate the median fluxes of  $1.3 \times 10^{-15}$ ,  $2.5 \times 10^{-16}$ , and  $1.7 \times 10^{-15}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  for the full, soft, and hard bands, respectively.

three standard bands. The X-ray fluxes in this survey span roughly 4 orders of magnitude, with  $\approx 50\%$  of the sources having soft-band and hard-band fluxes of less than  $2.5 \times 10^{-16}$  and  $1.7 \times 10^{-15}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ , respectively.

In Figure 9 we show “postage-stamp” images from the WFI *R*-band image with adaptively smoothed full-band contours overlaid for sources in the main *Chandra* catalog. The wide range of X-ray source sizes observed in these images is largely due to PSF broadening with off-axis angle. Figure 10a shows the positions of sources detected in the main *Chandra* catalog. The source density is highest close to the average aim point where the sensitivity is highest. Different symbol sizes represent different significances of source detection with *wavdetect* (see col. [48] of Table 2). New X-ray sources that are not present in the G02 or A03 main catalogs are indicated as filled circles; 135 new sources are detected, of which 15 lie outside the solid-angle coverage of the first  $\approx 1$  Ms exposure.

Figure 11 shows the band ratio as a function of full-band count rate for sources in the main *Chandra* catalog. We also derived average band ratios by stacking the individual sources together using a procedure similar to that of Lehmer et al. (2008). The average band ratio rises at lower count rates. The corresponding average photon index flattens from  $\Gamma \approx 1.8$  to  $\Gamma \approx 0.8$  for full-band count rates of  $\approx 10^{-2}$  to  $\approx 2 \times 10^{-4}$  counts  $\text{s}^{-1}$ . This trend has been reported in other studies (e.g., Tozzi et al. 2001; A03; L05) and is due to an increase in the number of absorbed AGNs detected at fainter fluxes. The average photon index does not continue getting flatter below full-band count rates of  $\approx 2 \times 10^{-4}$  counts  $\text{s}^{-1}$ , probably due to the increased contribution from normal and starburst galaxies at these lowest count rates (Bauer et al. 2004). In Figure 12a we show the WFI *R*-band magnitude versus soft-band flux for X-ray sources in the main catalog, as well as the approximate flux ratios for AGNs and galaxies (e.g., Maccacaro et al. 1988; Stocke et al. 1991; Hornschemeier et al. 2001; Bauer et al. 2004). More than half (304) of the X-ray sources lie in the region expected for AGNs, 74 of which are new sources. A significant minority (158) of the sources lie in the region for normal and starburst galaxies, 61 of which are new sources. The new sources have an increased fraction of normal and starburst galaxies. This source characterization, based only

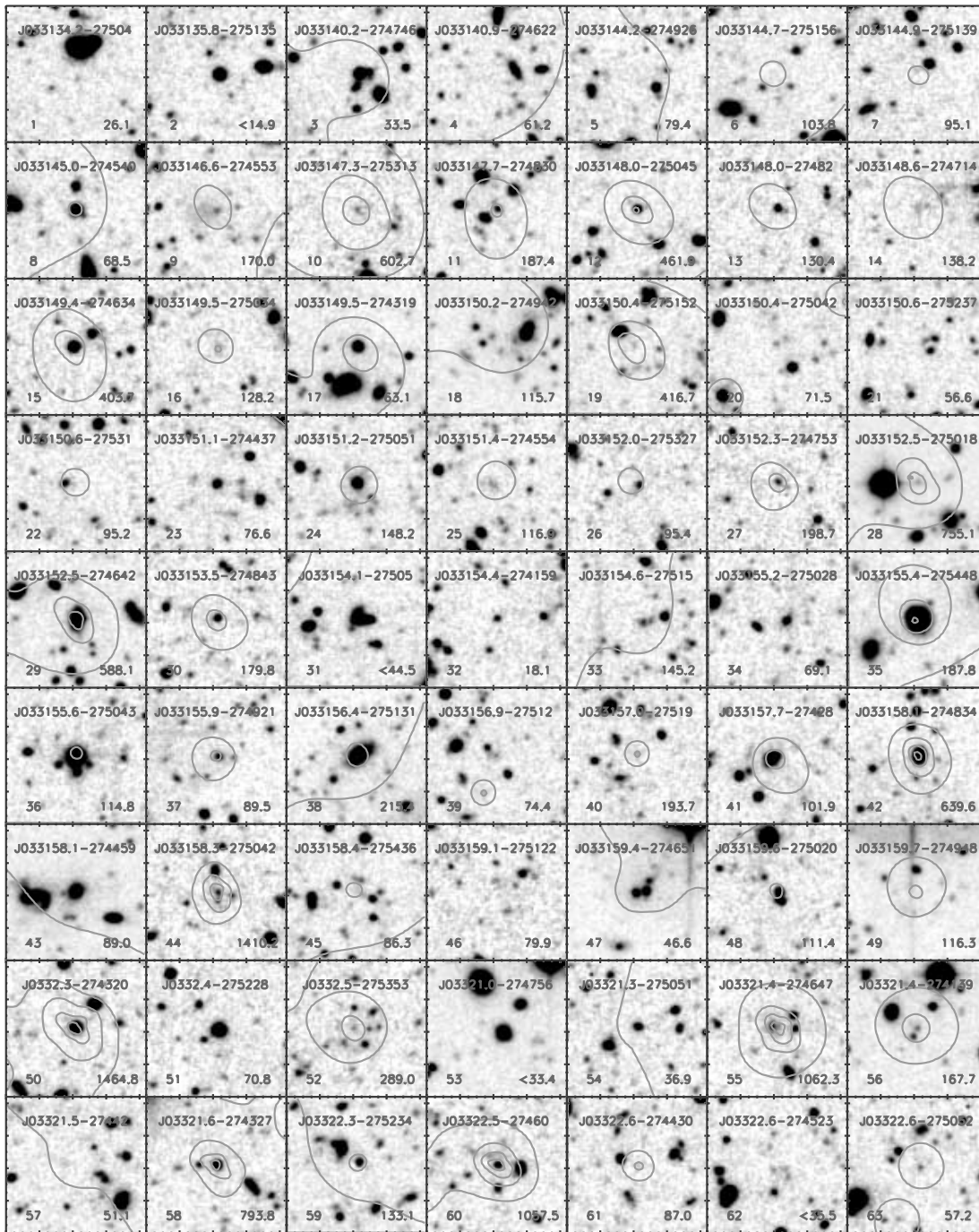


FIG. 9a

FIG. 9.—WFI *R*-band postage-stamp images for the sources in the main *Chandra* catalog with full-band adaptively smoothed X-ray contours overlaid. The contours are logarithmic in scale and range from  $\approx 0.003\%$  to  $30\%$  of the maximum pixel value. The label at the top of each image gives the source name, which is composed of the source coordinates, while numbers at the bottom left and right-hand corners correspond to the source number (see col. [1] of Table 2) and the full-band counts or upper limits (with a “<” sign) on the full-band counts, respectively. In several cases no X-ray contours are present, either because these sources were not detected in the full band or the full-band counts are low and *csmooth* has suppressed the observable emission in the adaptively smoothed images. Each image is  $25''$  on a side, and the source of interest is always located at the center of the image. Only one of the eight pages of cutouts is included here; all eight pages are available in the electronic edition. [See the electronic edition of the Supplement for panels 9b–9h of this figure.]

on the X-ray-to-optical flux ratio, is only approximate and will be refined in future studies.

### 3.3.2. Supplementary CDF-S Plus E-CDF-S *Chandra* Source Catalog

We can gain additional sensitivity in the outer portions of the  $\approx 2$  Ms CDF-S footprint by including the  $\approx 250$  ks E-CDF-S

(L05) observations. To this end, we processed and registered the E-CDF-S exposures in the same manner as our CDF-S observations. Notably, because of the different coverage of the CDF-S and E-CDF-S (see Fig. 2 of L05), the PSF sizes for the E-CDF-S near the average aim point for the CDF-S are substantially larger than those for the CDF-S. The E-CDF-S will likely only

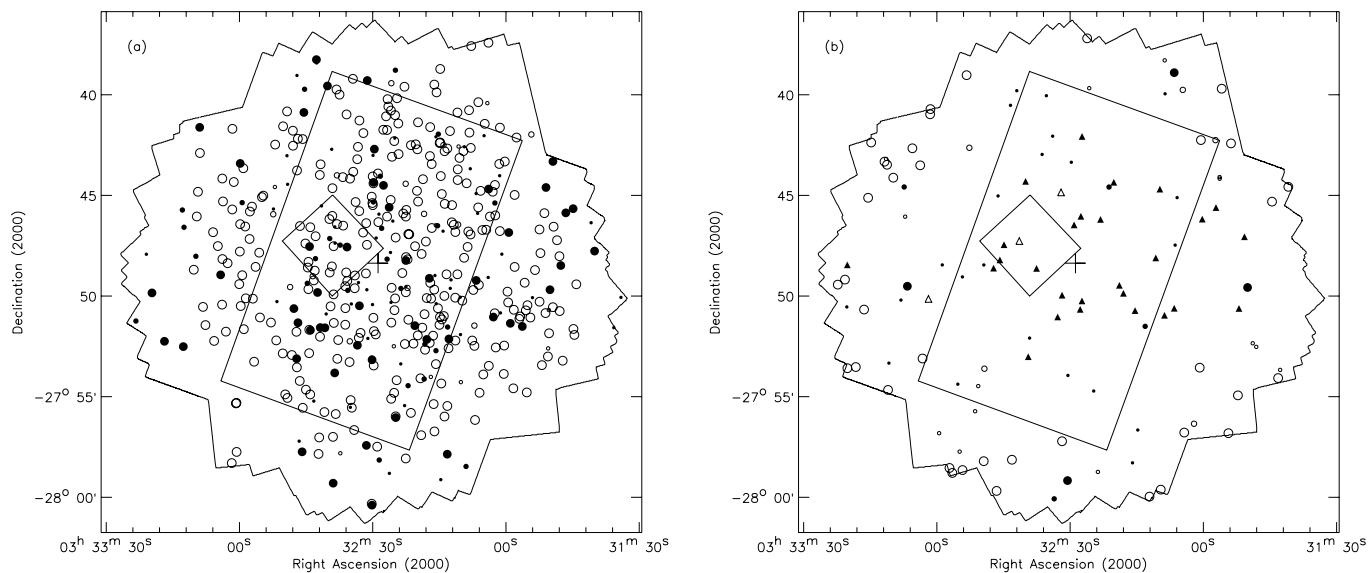


FIG. 10.—Positions of the sources in (a) the main *Chandra* catalog and (b) the supplementary *Chandra* catalogs. Circles represent X-ray sources in (a) the main *Chandra* catalog and (b) the supplementary CDF-S plus E-CDF-S *Chandra* catalog. Open circles represent X-ray sources that were previously detected in (a) the main catalogs of G02 or A03 and (b) the main catalogs of G02, A03, or L05. Filled circles represent new sources. Sizes indicate the maximum detection significance corresponding to *wavdetect* false-positive probability detection thresholds of  $1 \times 10^{-8}$  (large circles),  $1 \times 10^{-7}$  (medium circles), and  $1 \times 10^{-6}$  (small circles). Sources in the optically bright catalog are shown as open triangles (previously detected in the main catalog of A03) and filled triangles (new sources) in (b). For sources in the CDF-S plus E-CDF-S catalog, their detection significances are preferentially higher near the edge of the field due to the contribution of the E-CDF-S exposure. The regions and the plus sign have the same meaning as those in Fig. 1.

contribute additional background for all but the strongest sources around the center of the field. Thus, we excluded the E-CDF-S event lists within  $4'$  of the CDF-S average aim point. We also masked out portions of the E-CDF-S where the CDF-S exposure time was zero. Images and exposure maps were cropped in a similar manner.

We ran *wavdetect* with a false-positive probability threshold of  $1 \times 10^{-6}$  on the three standard-band images for the combined CDF-S plus E-CDF-S, detecting 86 sources not present in the main *Chandra* source catalog. The positions of these sources have been improved following the procedure described in § 3.3.1. Due to the drastically different overlapping PSFs, the derived properties of

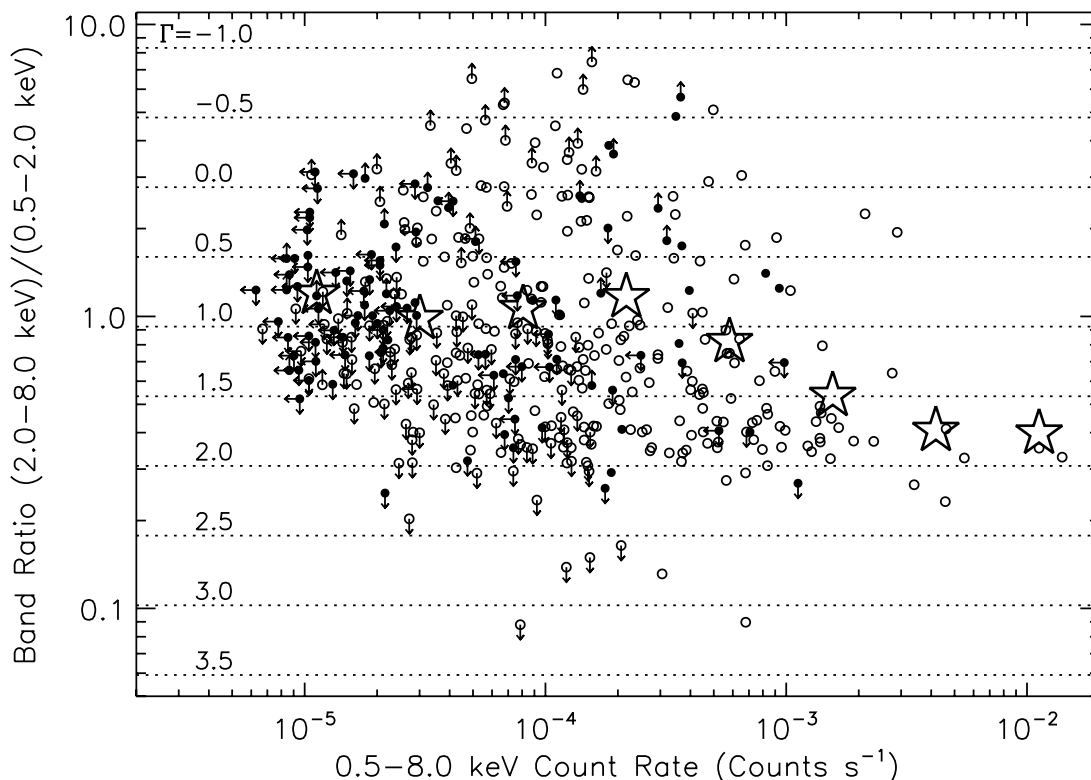


FIG. 11.—Band ratio vs. full-band count rate for sources in the main *Chandra* catalog. Open circles represent X-ray sources that were detected in the main catalogs of G02 or A03. Filled circles represent new sources. Plain arrows indicate upper or lower limits. Sources detected only in the full band cannot be plotted. The open stars show average band ratios as a function of full-band count rate derived from stacking analyses. Horizontal dotted lines show the band ratios corresponding to given effective photon indices; these were calculated using PIMMS.

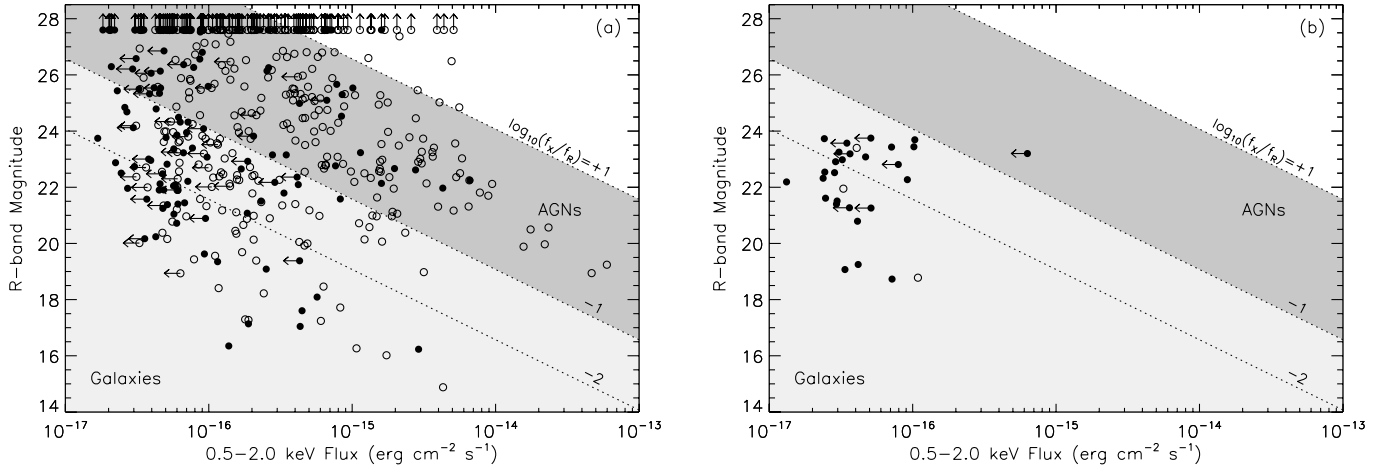


FIG. 12.—WFI *R*-band magnitude vs. soft-band flux for X-ray sources in (a) the main catalog and (b) the supplementary optically bright catalog. Open circles represent X-ray sources that were detected in the main catalogs of G02 or A03. Filled circles represent new sources. Sources without an optical counterpart are plotted as upward arrows. Diagonal lines indicate constant flux ratios. The shaded areas show the approximate flux ratios for AGNs (dark gray) and galaxies (light gray).

these X-ray sources are not as reliable as those in the main catalog. Therefore, we present these sources in Table 5 as a supplementary CDF-S plus E-CDF-S *Chandra* source catalog. For sources already detected in the E-CDF-S (L05), we took the photometry data from L05 directly. For new sources, photon counts and effective exposure times were extracted separately from the CDF-S and E-CDF-S data sets and then summed to give a total number of counts and a total effective exposure time. The format of Table 5 is very similar to that of Table 2, with a few details given below.

1. Columns (1)–(28): the format of these columns is exactly the same as that of columns (1)–(28) in Table 2, so the column descriptions in § 3.3.1 are applicable. Note that for sources detected in the E-CDF-S (see col. [29] or [52]), the source counts and their uncertainties were taken from L05 directly.

2. Column (29): the corresponding  $\approx 250$  ks E-CDF-S source number from the main *Chandra* catalog presented in L05 (see col. [1] of Table 2 in L05). We matched our X-ray source positions to L05 source positions using a matching radius that is the quadratic sum of the  $\approx 3 \sigma$  positional errors of the CDF-S and L05 X-ray sources. The  $3 \sigma$  positional error of a CDF-S source is approximately twice the positional error quoted in column (4), and that of an L05 source is approximately twice the positional error quoted in Table 2 of L05. Only one L05 match was found for each matched source. Sources with no L05 match have a value of  $-1$ .

3. Columns (30) and (31): the right ascension and declination of the corresponding L05 source indicated in column (29). Sources with no L05 match have right ascension and declination values set to “00 00 00.00” and “ $-00$  00 00.0.”

4. Columns (32)–(51): the format of these columns is exactly the same as that of columns (29)–(48) in Table 2, so the column descriptions in § 3.3.1 are applicable. Note that for sources detected in the E-CDF-S (see col. [29] or [52]), the source exposure times, band ratios, photon indices, and fluxes were taken from L05 directly.

5. Column (52): notes on the sources. “L” refers to sources that were detected in the  $\approx 250$  ks E-CDF-S (L05).

The 86 CDF-S plus E-CDF-S sources have effective exposures up to  $\approx 1.9$  Ms. Their positional uncertainties were estimated following equation (1), although the positional accuracy of the off-axis sources often have been improved due to the small PSF sizes of the E-CDF-S. Sixty ( $\approx 70\%$ ) of the sources have optical counterparts. Two of the 86 sources have counterparts in the A03 main catalog, and another two have counterparts in the G02 main catalog. In addition, 53 of the sources were detected in the main catalog of L05. There are thus 30 new sources in this supplementary catalog. Of these sources 50 ( $\approx 57\%$ ) and 41 ( $\approx 47\%$ ) are detected with false-positive probability thresholds of  $1 \times 10^{-7}$  and  $1 \times 10^{-8}$ , respectively.

Figure 10b shows the positions of sources detected in the supplementary CDF-S plus E-CDF-S catalog. Different symbol sizes represent different significances of the source detection with *wavdetect* (see col. [51] of Table 5).

### 3.3.3. Supplementary Optically Bright *Chandra* Source Catalog

Since the density of optically bright sources on the sky is comparatively low, we constructed a supplementary *Chandra* source

TABLE 5  
SUPPLEMENTARY CDF-S PLUS E-CDF-S *Chandra* CATALOG

No. (1)	X-RAY COORDINATES				COUNTS						
	$\alpha_{2000}$ (2)	$\delta_{2000}$ (3)	Pos Err (4)	Off-Axis (5)	FB (6)	FB Upp Err (7)	FB Low Err (8)	SB (9)	SB Upp Err (10)	SB Low Err (11)	
1.....	03 31 40.98	$-27$ 44 34.8	1.0	11.24	118.4	12.8	11.6	56.1	8.8	7.7	
2.....	03 31 42.76	$-27$ 53 40.7	1.6	11.47	17.4	5.9	4.7	7.5	4.2	3.0	
3.....	03 31 43.21	$-27$ 54 05.1	0.9	11.58	152.3	14.2	13.1	49.7	8.4	7.3	
4.....	03 31 44.64	$-27$ 45 19.1	1.2	10.23	39.9	8.1	6.9	7.5	$-1.0$	$-1.0$	
5.....	03 31 48.14	$-27$ 52 32.1	1.6	9.90	10.8	$-1.0$	$-1.0$	8.1	4.4	3.2	

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 5 is presented in its entirety in the electronic edition of the *Astrophysical Journal Supplement*. A portion is shown here for guidance regarding its form and content. The full table contains 52 columns of information on the 86 X-ray sources.

TABLE 6  
SUPPLEMENTARY OPTICALLY BRIGHT *Chandra* CATALOG

No. (1)	X-RAY COORDINATES				COUNTS					
	$\alpha_{2000}$ (2)	$\delta_{2000}$ (3)	POS ERR (4)	OFF-AXIS (5)	FB (6)	FB Upp Err (7)	FB Low Err (8)	SB (9)	SB Upp Err (10)	SB Low Err (11)
1.....	03 31 50.82	-27 47 03.8	1.2	8.50	47.2	-1.0	-1.0	22.1	5.8	4.7
2.....	03 31 52.03	-27 50 37.6	1.2	8.43	40.9	-1.0	-1.0	20.8	5.6	4.5
3.....	03 31 57.23	-27 45 36.9	1.2	7.51	41.6	-1.0	-1.0	22.7	5.8	4.7
4.....	03 32 00.32	-27 46 11.4	1.2	6.67	35.9	-1.0	-1.0	18.7	5.4	4.3
5.....	03 32 06.59	-27 50 37.3	1.2	5.39	24.3	-1.0	-1.0	12.0	4.6	3.4

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 6 is presented in its entirety in the electronic edition of the *Astrophysical Journal Supplement*. A portion is shown here for guidance regarding its form and content. The full table contains 38 columns of information on the 30 X-ray sources.

catalog including X-ray sources detected at a lower X-ray significance threshold than that used in the main catalog and having bright optical counterparts. We ran `wavdetect` with a false-positive probability threshold of  $1 \times 10^{-5}$  on the three CDF-S images, and we found 132 lower significance X-ray sources not present in the main *Chandra* source catalog or the supplementary CDF-S plus E-CDF-S catalog.

Bright optical sources were selected from the WFI *R*-band source catalog described in § 3.1, with an *R*-band magnitude brighter than 23.8. This *R*-band cutoff was empirically determined to provide a good balance between the number of detected sources and the expected number of false sources. We searched for bright optical counterparts to the low-significance X-ray sources using a matching radius of  $1.3''$ . A matching radius of  $1.3''$  was chosen as a compromise between having too few matches and too many false matches. In total 30 optically bright X-ray sources were found. We estimated the expected number of false matches by manually shifting the X-ray source coordinates in right ascension and declination by  $5.0''$  and  $10''$  (both positive and negative shifts) and recorrelating with the optical sources. On average, the number of false matches is  $\approx 3$  ( $\approx 10\%$ ), demonstrating that the majority of the 30 X-ray matches are real X-ray sources.

The supplementary optically bright *Chandra* source catalog is presented in Table 6. These sources typically have 4–35 counts in the band in which they were detected. The format of Table 6 is similar to that of Table 2, with the details of the columns given below.

1. Column (1): the source number. Sources are listed in order of increasing right ascension.

2. Columns (2) and (3): the right ascension and declination of the X-ray source, respectively. The `wavdetect` positions are used here for these faint X-ray sources. Whenever possible, we have quoted the position determined in the full band; when a source is not detected in the full band, we used, in order of priority, the soft-band position or hard-band position.

3. Column (4): the positional uncertainty. For these faint X-ray sources, the positional uncertainty is set to  $1.2''$ , the approximate 90th percentile of the optical–X-ray positional offsets given in column (17).

4. Column (5): the off-axis angle of the X-ray source in arcminutes (see col. [5] of Table 2 for details).

5. Columns (6)–(14): the source counts and the corresponding  $1 \sigma$  statistical errors (Gehrels 1986) or the upper limits on source counts for the three standard bands, respectively. When a source is detected in a given band, the photometry is taken directly from `wavdetect`. When a source is not detected, an upper limit is calculated (see cols. [6]–[14] of Table 2 for details).

6. Columns (15) and (16): the right ascension and declination of the optical counterpart.

7. Column (17): the measured offset between the optical and X-ray sources in arcseconds.

8. Column (18): the *R*-band AB magnitude of the optical counterpart.

9. Columns (19)–(26): the *i*-, *z*-, and *K<sub>s</sub>*-band AB magnitudes and the IRAC  $5.8 \mu\text{m}$  flux density of the optical counterpart, and the corresponding source ID in the optical and infrared catalogs (see cols. [19]–[26] of Table 2 for details).

10. Columns (27) and (28): the corresponding spectroscopic redshift and the reference for the redshift (see cols. [27] and [28] of Table 2 for details).

11. Column (29): the corresponding  $\approx 1$  Ms CDF-S source number from the main *Chandra* catalog presented in A03 (see col. [1] of Table 3a in A03). We used a matching radius that is the quadratic sum of the  $\approx 3 \sigma$  positional errors of the CDF-S and A03 X-ray sources. The  $3 \sigma$  positional error of a CDF-S source is  $\approx 1.3''$ , and that of an A03 source is approximately twice the positional error quoted in Table A2a of A03. Only one A03 match was found for each matched source. Supplementary sources with no A03 match have a value of  $-1$ . There are no matches to the main source catalog in G02, so we do not list the match results in this table.

12. Columns (30) and (31): the right ascension and declination of the corresponding A03 source indicated in column (29). Sources with no A03 match have right ascension and declination values set to “00 00 00.00” and “-00 00 00.0.”

13. Columns (32)–(34): the effective exposure times derived from the standard-band exposure maps.

14. Column (35): the photon index used to calculate source fluxes (cols. [36]–[38]). We used a constant photon index of  $\Gamma = 2.0$  since our source-selection technique preferentially selects objects with flux ratios  $f_{0.5-2.0 \text{ keV}}/f_R < 0.1$ , which are observed to have effective photon indices of  $\Gamma \approx 2$  (e.g., § 4.1.1 of Bauer et al. 2004).

15. Column (36)–(38): observed-frame fluxes in the three standard bands; quoted fluxes are in units of  $\text{ergs cm}^{-2} \text{ s}^{-1}$  and have been calculated assuming  $\Gamma = 2.0$ . The fluxes have not been corrected for absorption by the Galaxy or material intrinsic to the sources (see cols. [45]–[47] of Table 2 for details).

The WFI *R*-band magnitudes of these supplementary sources span  $R = 18.7$ – $23.8$ . In Figure 12b we show the *R*-band magnitude versus soft-band flux for the 30 optically bright X-ray sources. The approximate flux ratios for AGNs and galaxies are also plotted. The majority of the sources have the X-ray-to-optical flux ratios expected for normal and starburst galaxies. Some of

TABLE 7  
BACKGROUND PARAMETERS

BAND (keV)	MEAN BACKGROUND		TOTAL BACKGROUND <sup>c</sup> (10 <sup>5</sup> counts)	COUNT RATIO <sup>d</sup> (background/source)
	(counts pixel <sup>-1</sup> ) <sup>a</sup>	(counts Ms <sup>-1</sup> pixel <sup>-1</sup> ) <sup>b</sup>		
Full (0.5–8.0).....	0.248	0.242	16.1	9.7
Soft (0.5–2.0) .....	0.067	0.066	4.3	4.1
Hard (2–8).....	0.179	0.167	11.6	20.2

<sup>a</sup> The mean numbers of background counts per pixel. These are measured from the background images described in § 4.

<sup>b</sup> The mean numbers of counts per pixel divided by the mean effective exposure. These are measured from the exposure maps and background images described in § 4.

<sup>c</sup> Total number of background counts.

<sup>d</sup> Ratio of the total number of background counts to the total number of source counts.

these sources may be low-luminosity AGNs; only one source is detected in the hard band, suggesting that they are unlikely to be luminous absorbed AGNs. Note that the supplementary optically bright sources are not representative of the faintest X-ray sources as a whole, because our selection criteria preferentially select optically bright and X-ray faint non-AGNs (e.g., A03; Hornschemeier et al. 2003). The positions of the sources in the supplementary optically bright catalog are shown in Figure 10b.

#### 4. BACKGROUND AND SENSITIVITY ANALYSIS

Background maps were created for the three standard bands. We first masked out the point sources from the main *Chandra* catalog using apertures with radii twice that of the  $\approx 90\%$  PSF encircled-energy radii; approximately 12% of the pixels were masked out. The resulting images should include minimum contributions from detected point sources. However, they also include contributions from a few extended sources (e.g., Bauer et al. 2002), which cause a slight overestimation of the measured background. Even with a  $\approx 2$  Ms exposure, about 79% of the pixels have no background counts in the full band. For such a small number of detected counts per pixel, the expected counts distribution is Poissonian. We compared the background-count distributions to Poisson distributions with the mean number of background counts per pixel using the Kolmogorov-Smirnov test, and we found them to be very similar in all three standard bands for various regions across the survey field (see § 4.2 of A03 for more details on the tests). We filled in the masked regions for each source with a local background estimate by constructing a probability distribution of counts using an annulus with inner and outer radii of 2 and 4 times the  $\approx 90\%$  PSF encircled-energy radius, respectively. The background properties are summarized in Table 7. The total background includes contributions from the unresolved cosmic background, particle background, and instrumental background (e.g., Markevitch 2001; Markevitch et al. 2003). For our analyses we are only interested in the total background and do not distinguish between these different components. The mean background count rates are  $\approx 20\%$ – $30\%$  higher compared to the  $\approx 2$  Ms CDF-N (A03) or the  $\approx 250$  ks E-CDF-S (L05), which are reasonable variations given the variability of the particle and instrumental background components over the past several years.

The faintest sources in the main *Chandra* catalog have  $\approx 5$  counts in the soft band and  $\approx 8$  counts in the hard band (see Table 3). For a  $\Gamma = 1.4$  power law with Galactic absorption, the corresponding soft-band and hard-band fluxes at the average aim point are  $\approx 1.6 \times 10^{-17}$  and  $\approx 9.0 \times 10^{-17}$  ergs cm<sup>-2</sup> s<sup>-1</sup>, respectively. This provides an estimate of the ultimate sensitivity of this survey. However, these numbers are only relevant for a small area close to the average aim point. To determine the sen-

sitivity across the field, it is necessary to take into account the broadening of the PSF with off-axis angle, as well as changes in the effective exposure and background rate across the field. Following L05, we estimated the sensitivity across the field by employing a Poisson model. The resulting relation can be approximately represented by

$$\log N = \alpha + \beta \log b + \gamma(\log b)^2 + \delta(\log b)^3, \quad (2)$$

where  $N$  is the required number of counts for detection and  $b$  is the number of background counts in a source cell;  $\alpha = 0.917$ ,  $\beta = 0.414$ ,  $\gamma = 0.0822$ , and  $\delta = 0.0051$  are fitting constants. For the sensitivity calculations here, we measured the number of background counts  $b$  in the background maps using an aperture size of 70% of the PSF encircled-energy radius. The 70% encircled-energy radius was chosen as a compromise between having too few source counts and too many background counts.

Following equation (2), we constructed sensitivity maps using the background and exposure maps, assuming a  $\Gamma = 1.4$  power-law model with Galactic absorption. Since we do not filter out detected sources with our sensitivity maps, a small fraction of sources have fluxes slightly below these sensitivity limits (four sources in the full band, 14 sources in the soft band, and seven sources in the hard band). The full-band sensitivity map is shown in Figure 13,

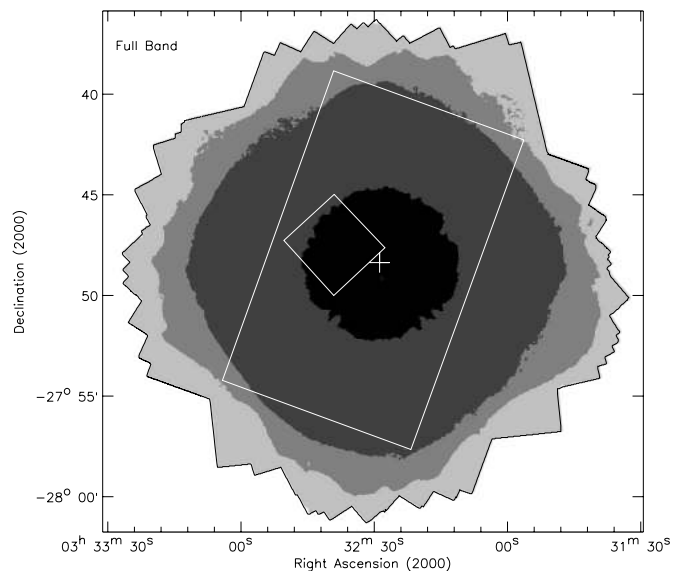


FIG. 13.—Full-band sensitivity map of the 2 Ms CDF-S. This sensitivity map has been created following § 4. The gray-scale levels (from black to light gray) represent areas with flux limits (in units of ergs cm<sup>-2</sup> s<sup>-1</sup>) of  $<10^{-16}$ ,  $10^{-16}$  to  $3.3 \times 10^{-16}$ ,  $3.3 \times 10^{-16}$  to  $10^{-15}$ , and  $>10^{-15}$ , respectively. The regions and the plus sign have the same meaning as those in Fig. 1.



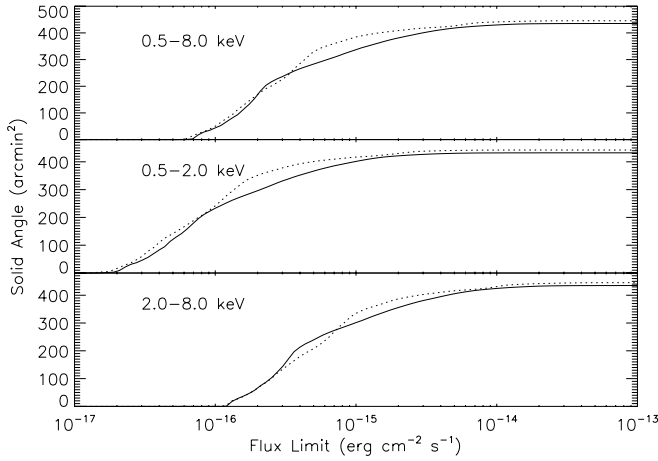


FIG. 14.—Survey solid angle as a function of the flux limit for the full (*top*), soft (*middle*), and hard (*bottom*) bands, determined following § 4. Data are plotted as solid curves for the  $\approx 2$  Ms CDF-S and as dotted curves for the  $\approx 2$  Ms CDF-N. The flux limits at the average aim point of the CDF-S are  $\approx 7.1 \times 10^{-17}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  (full band),  $\approx 1.9 \times 10^{-17}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  (soft band), and  $\approx 1.3 \times 10^{-16}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  (hard band).

and in Figure 14 we show plots of solid angle versus flux limit for the full, soft, and hard bands. The  $\approx 1$  arcmin<sup>2</sup> region at the average aim point has soft-band and hard-band sensitivity limits of  $\approx 1.9 \times 10^{-17}$  and  $\approx 1.3 \times 10^{-16}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ , respectively. Solid angles for the  $\approx 2$  Ms CDF-N have been plotted for comparison in Figure 14 (*dotted curves*), which appear to be similar to those for the CDF-S.<sup>28</sup>

## 5. NUMBER COUNTS FOR THE MAIN CHANDRA CATALOG

Cumulative number counts,  $N(>S)$ , for the soft and hard bands were calculated for the  $\approx 2$  Ms CDF-S. To quantify the effects of incompleteness and bias, we took a similar approach to the one in Bauer et al. (2004) and created 200 Monte Carlo simulated observations in both the soft and hard bands. We added simulated sources at random positions to the background maps described in § 4. The fluxes of these simulated sources were drawn randomly from the total number-count models of Moretti et al. (2003) between  $1.6 \times 10^{-17}$  and  $10^{-11}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  in the soft band and  $9 \times 10^{-17}$  and  $10^{-11}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  in the hard band. These fluxes were converted to X-ray photon counts using the exposure maps and a photon index of  $\Gamma = 1.4$ . Statistical errors were added to the counts to account for the effect of Eddington bias. Finally, counts for each simulated source were added to the background map following a PSF probability distribution function derived from the combined model PSF of the nearest real X-ray source in the main catalog. These model PSFs were produced using AE.

Source searching and photometry were performed on the simulated images using the same method as that used to produce the main catalog. A completeness correction factor ( $F$ ) was estimated by comparing the number of simulated input sources with the number of simulated detected sources as a function of detected counts. A flux recovery correction factor ( $R$ ) was calculated by comparing the simulated input counts with simulated measured counts. The correction factors are position- and count-dependent. For each of the 462 X-ray sources in the main catalog, we deter-

mined the two correction factors based on a sample of simulated sources within  $2'$  of the source position and having similar exposure times. Sources close to the edge of the survey field are not well sampled, and thus we calculated cumulative number counts using only the 428 X-ray sources that are located within  $10'$  of the average aim point. The completeness and flux recovery corrections remain close to unity above  $\sim 50$ – $100$  counts. Below this point, *Chandra*'s varying PSF size and spatially dependent vignetting begin to affect source detection and photometry.

We set our minimum flux levels to  $3 \times 10^{-17}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  in the soft band and  $2.5 \times 10^{-16}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  in the hard band. These limits were chosen since at lower fluxes there are less than 10–15 additional sources contributing to the number counts, and thus, the number counts at fainter levels have large uncertainties. The cumulative number of sources,  $N(>S)$ , brighter than a given flux,  $S$ , weighted by the appropriate aerial coverage, is

$$N(>S) = \sum_{S_i > S} (F_i \Omega_i)^{-1}, \quad (3)$$

where  $\Omega_i$  is the maximum solid angle for which a source with flux,  $S_i$ , could be detected. Each flux  $S$  has been corrected for flux bias assuming

$$S_i = R_i S_i^0, \quad (4)$$

where  $S_i^0$  is the original flux quoted in the main catalog. The maximum solid angles were computed using the inner  $10'$  radius regions of the sensitivity maps. We have also calculated  $1 \sigma$  errors for the cumulative distributions following Gehrels (1986).

Figure 15 displays the cumulative number counts and the corresponding  $1 \sigma$  errors for the main *Chandra* catalog. Cumulative number counts for several other surveys have also been shown for comparison. The derived  $\approx 2$  Ms CDF-S cumulative number counts are in general agreement with previous survey results for the  $\approx 1$  Ms CDF-S (Rosati et al. 2002) and the  $\approx 250$  ks E-CDF-S (L05), at around the  $1 \sigma$  confidence level over the entire flux range in the soft and hard bands. The apparent deviation between the  $\approx 2$  Ms and  $\approx 1$  Ms CDF-S soft-band number counts mainly comes from the difference in the count-rate-to-flux conversion factor used in these two surveys.<sup>29</sup> The *XMM-Newton* observations in the COSMOS field (Cappelluti et al. 2007) provide similar number counts, although not as deep as the CDF-S observations.

To make a consistent comparison with the  $\approx 2$  Ms CDF-N number counts, we analyzed the CDF-N observations in the same way as in this paper. A main catalog of 575 X-ray sources was constructed. Number counts were calculated using the 496 X-ray sources located within  $10'$  of the average aim point, and these have been corrected for incompleteness and flux bias based on simulations. The CDF-N cumulative number counts are presented in Figure 15 (*dotted curves*), along with the ratios of the CDF-S to CDF-N number counts. In the soft band, the  $\approx 2$  Ms CDF-S number counts appear to be consistent with those for the  $\approx 2$  Ms CDF-N to within  $\approx 1 \sigma$  at fluxes above  $\approx 2 \times 10^{-16}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ . Small differences (up to  $\approx 3 \sigma$ ) exist at fainter fluxes. In the hard band, the CDF-N number counts deviate above the  $1 \sigma$  errors

<sup>28</sup> The CDF-N sensitivity limits were calculated following the same method described above.

<sup>29</sup> An average photon index of  $\Gamma = 1.4$  was used to calculate fluxes in Rosati et al. (2002), while in this survey, the photon index was estimated for each source separately and so was the count-rate-to-flux conversion factor (see § 3.3.1). We did a test by calculating the soft-band fluxes using the conversion factor given by Rosati et al. (2002). The derived fluxes are  $\sim 90\%$  of those presented in the main catalog, and the resulting soft-band number counts are consistent with those for the  $\approx 1$  Ms CDF-S to within  $1 \sigma$ .

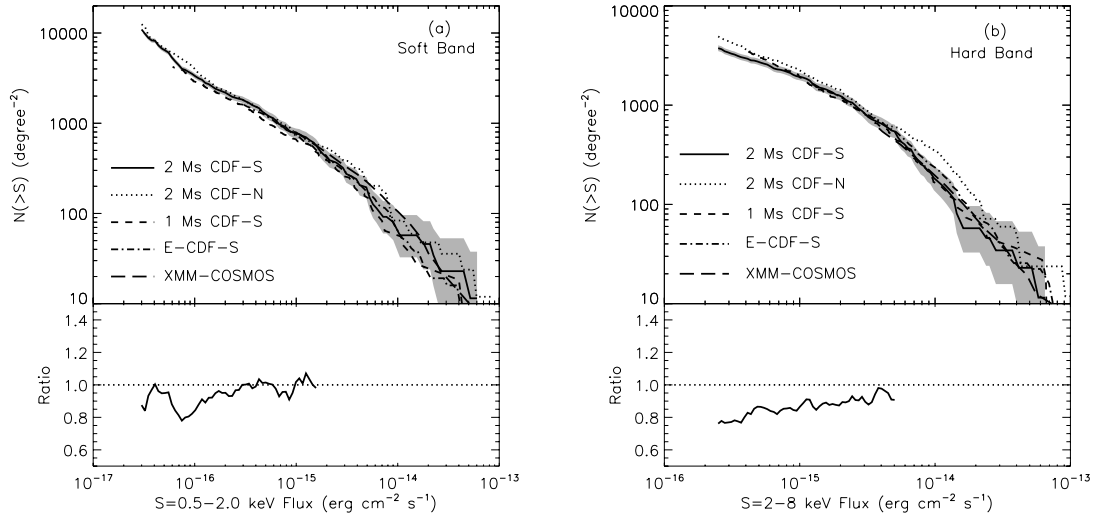


FIG. 15.—*Top*: Number of sources,  $N(>S)$ , brighter than a given flux,  $S$ , for the (a) soft band and (b) hard band. The  $\approx 2$  Ms CDF-S data are plotted as black solid curves with the  $1\sigma$  errors plotted as gray shaded areas. The cumulative number counts were computed using 428 X-ray sources in the main *Chandra* catalog that are located within  $10'$  of the average aim point and have been corrected for incompleteness and flux bias. Also shown are the cumulative number-count results for the  $\approx 2$  Ms CDF-N (dotted curves), the  $\approx 1$  Ms CDF-S (dashed curves; Rosati et al. 2002), the  $\approx 250$  ks E-CDF-S (dash-dotted curves; L05), and *XMM-Newton* observations in the COSMOS field (long-dashed curves; Cappelluti et al. 2007). The 2–10 keV fluxes in the  $\approx 1$  Ms CDF-S and the COSMOS field were converted to 2–8 keV fluxes assuming a photon index  $\Gamma = 1.4$ . *Bottom*: Ratio of the CDF-S to CDF-N cumulative number counts for the (a) soft band and (b) hard band. Ratios were calculated only for number counts that were derived from a sample of  $\geq 50$  sources, since for smaller numbers of sources there are large statistical errors. This corresponds to soft-band fluxes  $\leq 1.5 \times 10^{-15}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  and hard-band fluxes  $\leq 5 \times 10^{-15}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ . [See the electronic edition of the Supplement for a color version of this figure.]

of the CDF-S number counts at fluxes below  $\approx 2 \times 10^{-15}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ ; the difference at the faintest fluxes is  $\approx 25\%$  ( $\approx 3\sigma$ ). Similar findings of differences between the CDF-N and CDF-S number counts have been reported in previous studies (e.g., Cowie et al. 2002; Moretti et al. 2003; Bauer et al. 2004), and it appears that this results from small field-to-field variations. Such field-to-field variations are generally believed to arise from the large-scale structure underlying the cosmic X-ray-source distribution (e.g., Gilli et al. 2003; Yang et al. 2003).

## 6. SUMMARY

We have presented catalogs and basic analyses of X-ray point sources detected in the  $\approx 2$  Ms CDF-S, which is one of the two deepest *Chandra* surveys. The key points from this work are the following:

1. The entire CDF-S consists of 23 separate observations with 1.911 Ms of combined exposure. The survey covers an area of 435.6 arcmin<sup>2</sup>.
2. The main *Chandra* source catalog consists of 462 sources that were detected using *wavdetect* with a false-positive probability threshold of  $1 \times 10^{-6}$ . These sources were detected in up to three X-ray bands: 0.5–8.0 keV, 0.5–2.0 keV, and 2–8 keV; 135 of these sources are new.
3. The first supplementary *Chandra* source catalog contains 86 sources that were generated by merging the  $\approx 250$  ks E-CDF-S with the CDF-S, which provides additional sensitivity in the outer regions of the CDF-S.
4. The second supplementary *Chandra* source catalog contains 30 sources that were detected at a lower X-ray significance threshold of  $1 \times 10^{-5}$  and that have bright optical counterparts ( $R < 23.8$ ).
5. Source positions for the main and supplementary CDF-S plus E-CDF-S *Chandra* catalogs have been determined using centroid and matched-filter techniques; the median positional uncertainty is  $\approx 0.36''$ .

6. The basic X-ray and optical properties of the point sources indicate a variety of source types. More than half of the sources in the main *Chandra* catalogs appear to be AGNs. Of the 135 newly detected sources,  $\approx 55\%$  appear to be AGNs, while  $\approx 45\%$  appear to be starburst and normal galaxies. The majority of the sources in the supplementary optically bright catalog are expected to be normal and starburst galaxies.

7. The average backgrounds in the 0.5–2.0 and 2–8 keV bands are 0.066 and 0.167 counts  $\text{Ms}^{-1} \text{pixel}^{-1}$ , respectively. Thus, these observations are nearly photon limited near the aim point and could be extended to substantially greater depths with further exposure. The background count distributions are very close to Poisson distributions. The on-axis flux limits in the 0.5–2.0 and 2–8 keV bands are  $\approx 1.9 \times 10^{-17}$  and  $\approx 1.3 \times 10^{-16}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ , respectively.

8. Compared to the other deepest *Chandra* survey, the  $\approx 2$  Ms CDF-N, the CDF-S has similar effective exposure coverage and sensitivity limits. The cumulative number counts of these two fields are consistent with each other to within  $\approx 1\sigma$  at fluxes above  $\approx 2 \times 10^{-16}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  in the soft band. The CDF-N number counts are up to  $\approx 25\%$  higher than the CDF-S number counts at the faintest fluxes in the soft and hard bands, indicating small field-to-field variations.

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