BLACK HOLES THROUGH COSMIC TIME:
Exploring the distant X-ray Universe with extragalactic Chandra surveys
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Fig. 1.— X-ray images and survey areas for a few representative Chandra surveys: XBoötes (Murray et al. 2005), C-COSMOS (Elvis et al. 2009), AEGIS-X (Nandra et al. 2005), and the Chandra Deep Field-North (Alexander et al. 2003). The relative areas of each field are superposed on the XBoötes image, and survey exposure times are shown. (The three fields cover separate areas, and are shown together only for comparison.) The full C-COSMOS image is shown on an expanded scale. The inset illustration shows an active galactic nucleus; the vast majority of the X-ray sources detected in Chandra surveys are AGN. (Figure prepared by author, AGN illustration by NASA/JPL-Caltech/T. Pyle-SSC.)
In the last decade we have seen profound advances in our understanding of the composition and evolution of the Universe. Prominent among these is the discovery that essentially all galaxies with stellar bulges contain supermassive black holes (SMBH), which are believed to be the relics of accretion in active galactic nuclei (AGN). Further, the masses of SMBHs are tightly correlated to the properties of their host bulges, and the energy released by AGN may have a significant effect on the star formation history of galaxies. Thus it is increasingly clear that growth and evolution of black holes and galaxies are linked through cosmic time.

X-ray surveys are exceptionally powerful tools for studying the evolution of black holes and their host galaxies, by detecting large numbers of AGN over a wide range of redshifts and cosmic environments from voids to groups and clusters. With its superb angular resolution, low background, and sensitivity in the energy range 0.5–8 keV, Chandra has been at the forefront of recent extragalactic surveys. In this article we provide an overview of some of the leading Chandra surveys, and describe some recent results on the composition of the cosmic X-ray background (CXB), the evolution of black hole accretion, the nature of AGN populations, and links between AGN and their host galaxies and environments. This is an extremely active and exciting field, with many key contributions made by XMM-Newton, Suzaku, INTEGRAL, Swift, and other space and ground-based observatories; here we will focus on just a few representative results from Chandra surveys.

**Breadth and depth in Chandra surveys**

Chandra extragalactic surveys range from very deep and narrow to shallow and very wide, allowing us to study the broadest possible range in redshift and luminosity (Fig. 1). The deepest existing X-ray surveys are the Chandra Deep Fields (CDFs) North (Alexander et al. 2003) and South (Luo et al. 2008), each with 2 Ms total exposure. Owing to Chandra’s unparalleled spatial resolution, these observations are not limited by confusion and probe to depths more than 6 times fainter than is accessible with any other X-ray observatory. The CDFs have yielded extraordinary progress in understanding faint X-ray populations and resolving the CXB. However, the X-ray luminosity density is dominated by more luminous X-ray sources that are rare in the CDFs, so Chandra also has undertaken several shallower surveys over wider areas to study these objects. These surveys include, in order of increasing area, ELAIS-N (Manners et al. 2003), the Extended CDF-S (Lehmer et al. 2005), AEGIS-X (Nandra et al. 2005), CLASXS and CLANS (Trouille et al. 2008) (CLANS is comprised of data from the SWIRE/Chandra Survey; Wilkes et al. 2009), C-COSMOS (Elvis et al. 2009), XDEEP2 (Murray et al. 2008) and XBoötes (Murray et al. 2005). The areas and corresponding flux limits for these surveys are shown in Fig. 2. Most surveys also have extensive multiwavelength coverage with HST, Spitzer, ground-based optical imaging and spectroscopy, radio, and other observations (Fig. 3), allowing us to understand the detailed spectral energy distributions (SEDs) and environments of the X-ray sources. For a more detailed review of
Fig. 2.— Chandra surveys span a wide range of depths and areas, in order to probe the widest possible ranges in redshift, luminosity, and environment. The figure shows limiting 0.5–2 keV flux versus area for various Chandra blank-field and serendipitous extragalactic surveys (see text for references). Since sensitivity varies across Chandra fields, for a given survey the area increases with increasing flux limit. Lines show the sensitivity curves between 25% and 75% of the total area of each survey. Solid lines show contiguous surveys, dotted lines show serendipitous surveys, and dashed lines show surveys comprised of two or three separate fields with similar depths and multiwavelength coverage. Flux limits are defined somewhat differently for different surveys, but generally correspond to a $\sim50\%$ completeness limit. For SEXSI (which is a hard X-ray selected serendipitous survey) the 2–10 keV limiting fluxes were converted from 0.5–2 keV by dividing by 6.5, corresponding roughly to the relative on-axis flux limits of the CDF-N in the soft and hard bands. The AEGIS-X and XBoötes sensitivities correspond to the 200 ks and 5 ks surveys, respectively, while the sensitivity for the $\approx10$ ks XDEEP2 exposures is estimated from XBoötes.

X-ray surveys with a focus on the deepest fields, see Brandt & Hasinger (2005).

In addition to dedicated Chandra observations in contiguous survey fields, the Chandra Multiwavelength Project (ChaMP) uses archival data for optical imaging and spectroscopic followup of serendipitous sources from 392 (non-contiguous) ACIS pointings (Green et al. 2004; Kim et al. 2007). The large samples nevertheless allow removal of potentially biasing PI-targeted objects, and large statistical subsamples immune to cosmic variance. Similar follow-up of serendipitous hard X-ray (2–10 keV) sources has been undertaken by the Serendipitous Extragalactic X-ray Source Identification (SEXSI) program (Harrison et al. 2003).
Resolving the cosmic X-ray background

Since its discovery in rocket flights at the dawn of X-ray astronomy (Giacconi et al. 1962), the origin of the diffuse extragalactic X-ray background has been one of the leading questions in high-energy astrophysics. With the exceptional sensitivity of the CDFs, it is now clear that almost all of the extragalactic CXB at energies $< 2$ keV arises from X-ray point sources. The primary contributors are AGN, which dominate the radiative energy density of the Universe at X-ray wavelengths.

The precise fraction of the CXB that is resolved in X-rays has been the subject of numerous studies. Moretti et al. (2003) summed the X-ray emission from sources detected in a variety of Chandra and other surveys, and compared the total to an estimate of the total CXB, concluding that $\approx 90\%$ of the CXB at $E < 2$ keV was resolved. Worsley et al. (2005) performed a similar analysis as a function of energy, and showed that the resolved fraction drops at energies $> 5$ keV, indicating a “missing” population of hard sources, which may include AGN that are highly obscured by intervening gas (see below). Hickox & Markevitch (2006) took a complementary approach, measuring the absolute flux of the unresolved CXB in the CDFs, and showed that the resolved fraction of the 1–2 keV CXB is $\approx 80\%$. 

Fig. 3.— Optical counterparts of X-ray sources in the CDF-N as detected in the Hubble Deep Field (HDF). Shown is the full HDF image, and circles show objects matched with X-ray sources in the 2 Ms CDF-N. (From Chandra press release; Credit: NASA/Penn State.)
Hickox & Markevitch (2007b) further demonstrated that only 7% $\pm$ 3% of the 1–2 keV CXB remained unresolved after excluding HST sources in the GOODS field, in broad agreement with a stacking analysis by Worsley et al. (2006). By studying the distribution of X-ray counts at the HST source positions, Hickox & Markevitch (2007a) showed that the $\log N$-$\log S$ for faint, unresolved X-ray galaxies in the CDFs is consistent with an extension of the observed population of faint star-forming galaxies, rather than AGN. These results indicate a large population of faint X-ray sources that may be accessible with deeper observations in the CDFs.

The cosmic evolution of black hole growth

A key question in black hole evolution is: where and when did black holes gain their mass? Unlike galaxies (for which we can determine ages for the stars), black holes have no “memory” of their formation history. Therefore, to determine the cosmic evolution of black hole growth we must observe that growth directly, by measuring how the space density of accreting black holes evolves with cosmic time. A number of authors have used the wealth of spectroscopic redshifts available in X-ray surveys to derive the X-ray luminosity function for AGN at a range of redshifts from the local Universe to $z > 4$ (e.g., Ueda et al. 2003; Barger et al. 2005; Hasinger et al. 2005; Silverman et al. 2008a). To cover the largest possible region in the luminosity-redshift plane, these studies combine data from narrow, deep and wide, shallow Chandra surveys, as well as data from XMM-Newton ASCA, ROSAT, and other missions.

These studies have shown that AGN activity has a relatively complex and interesting evolution with redshift. Chandra results favor a model of luminosity-dependent density evolution (LDDE), in which the number density of AGN evolves differently for sources of varying luminosities. These results provide evidence for downsizing, in which the density of the most luminous AGN peaks earlier in cosmic time than for less luminous objects (e.g., Steffen et al. 2003; Hasinger et al. 2005; see Fig. 4), which can be shown to imply that large black holes are formed earlier than their low-mass counterparts (e.g., Merloni & Heinz 2008; Shankar et al. 2009). Qualitatively similar downsizing has been observed for star formation in galaxies (e.g., Cowie et al. 1996), providing a circumstantial link between SMBH and galaxy evolution.

Understanding X-ray source populations

The large numbers of AGN detected in extragalactic surveys allows for robust statistical studies of AGN populations. Particular effort has been focused on measurements of X-ray spectra, which provide insights into the nature of AGN accretion. Tozzi et al. (2006) performed spectral fits for hundreds of sources in the CDF-S, while Green et al. (2009) measured the spectra for $> 1000$ SDSS quasars in ChaMP, including 56 with $z > 3$. These studies show that in general, the unabsorbed spectra of AGN have remarkably uniform power-law continua. However, Chan-
dra studies also have shown that X-ray spectra and X-ray to UV SEDs of AGN get harder with decreasing Eddington ratios (e.g., Steffen et al. 2006; Kelly et al. 2008), similarly to black hole X-ray binaries (Remillard & McClintock 2006).

X-ray surveys also can constrain the numbers of AGN that are absorbed by intervening gas, which preferentially absorbs low-energy X-rays and so hardens the observed spectrum. The total spectrum of the CXB is harder than the emission from a typical unabsorbed AGN, indicating a significant contribution from absorbed sources. In the local Universe, 75% or more of optically selected Seyfert galaxies are obscured by dust (Maiolino & Rieke 1995), and Chandra surveys suggest a similar fraction are absorbed in X-rays. Further, there is evidence that the obscured fraction rises lower luminosities and may increase at higher redshifts (e.g., Ueda et al. 2003; Steffen et al. 2003; Hasinger 2008), which may constrain models in which AGN provide radiation pressure feedback on surrounding gas. In addition, X-ray studies have confirmed the identification of obscured AGN detected in optical and IR observations (e.g., Hickox et al. 2007; Polletta et al. 2008; Donley et al. 2008; Alexander et al. 2008b).

Using the observed luminosity functions, spectral shapes, and absorbing columns derived from X-ray, optical, and infrared surveys, we can estimate the number of AGN that are obscured by dust. This information is crucial for understanding the role of AGN in the evolution of galaxies and the universe. The Eddington ratio is defined as the ratio of bolometric accretion luminosity to the Eddington limit, where $L_{\text{Edd}} = 1.3 \times 10^{38} \left(\frac{M_{\text{BH}}}{M_\odot}\right) \text{erg s}^{-1}$. 

Fig. 4.— The comoving space density of X-ray AGN as a function of redshift, shown in the (b) 0.5–2 keV band (Hasinger et al. 2005) and (b) 2–10 keV band (Ueda et al. 2003). Lines show the evolution of AGN space density in different bins of luminosity. The data favor LDDE models, in which the space density of low-luminosity AGN peaks at a lower redshift compared to high-luminosity objects. Figure compiled by Brandt & Hasinger (2005).
from Chandra and other surveys, it has been possible to model the spectrum of the total cosmic X-ray background (e.g., Treister & Urry 2005; Gilli et al. 2007). While these models still have significant uncertainties (particularly in the number of highly obscured AGN), their success implies that we may be converging on a coherent picture for the cosmic evolution of black hole growth. One caveat however, is that the low numbers of X-ray counts in surveys make it difficult to distinguish absorption from intrinsically hard spectra for faint sources. If the X-ray spectra of AGN become harder at low Eddington ratio, this could produce a large number of low-luminosity, X-ray hard AGN that would be classified as “absorbed” in current analyses (Hopkins et al. 2009). Future deep surveys or detailed stacking of X-ray spectra may be able to break the degeneracy between intrinsic spectral shape and absorbing column.

**Links between AGN and galaxy evolution**

Finally, Chandra surveys have allowed for detailed examination of the host galaxies and environments and X-ray AGN, providing insight on the role of AGN in the evolution of galaxies. One powerful diagnostic is the color-luminosity distribution for the galaxies that host AGN. Galaxies are known to be divided into two types in color-magnitude space: the red sequence of luminous, passively evolving galaxies, and the blue cloud of less luminous, star-forming systems. Interestingly, a number of Chandra studies have found that at \( z \lesssim 1 \), luminous X-ray AGN (unlike radio, optical, or infrared-selected AGN) are preferentially found in the “green valley”, with colors intermediate between blue and red galaxies (e.g., Nandra et al. 2007; Georgakakis et al. 2008; Silverman et al. 2008b; Hickox et al. 2009; see Fig. 5), indicating that X-ray AGN may be associated with the transition of galaxies from the blue cloud to the red sequence, and may be responsible for quenching the star formation in galaxies through feedback (Bundy et al. 2008; Georgakakis et al. 2008). Further, studies of the environments and clustering of AGN find that Chandra X-ray AGN are preferentially found in overdense regions characteristic of galaxy groups (e.g., Yang et al. 2006; Georgakakis et al. 2007; Silverman et al. 2009; Hickox et al. 2009; Coil et al. 2009). Models suggest that it is these environments where star formation shuts off in massive galaxies; AGN may play a role in the initial quenching of star formation, or in subsequent heating that prevents gas from cooling and further forming stars (e.g., Croton et al. 2006; Bower et al. 2006; Hopkins et al. 2008).

Chandra surveys also have explored the presence of AGN associated with massive, vigorously star-forming galaxies in the distant Universe (\( z \sim 2 \)). X-ray studies of starburst galaxies selected in the CDFs with observations in the submillimeter (e.g., Alexander et al. 2005) and infrared (Daddi et al. 2007; Fiore et al. 2008) have provided evidence for a large density of highly obscured AGN in galaxies co-eval with the formation of the bulk of their stellar mass. Alexander et al. (2008a) found that the AGN in submm galaxies have black hole masses that are roughly consistent with those expected from the local relation between black hole mass and bulge mass, indicating
Fig. 5.—(a) Optical colors and absolute magnitudes of AGNs at $0.25 < z < 0.8$ from the AGES redshift survey in Boötes (Hickox et al. 2009). Contours and black points show normal galaxies, and lines separate red and blue galaxies. The three panels show radio, X-ray, and IR-selected AGNs, respectively. (b) Distribution in rest-frame optical color for AGNs selected in the three wavebands, compared to normal galaxies at $0.25 < z < 0.8$ (thick gray line). The radio AGN color distribution peaks along the red sequence, while X-ray AGNs are found preferentially in the “green valley” between the red sequence and the blue cloud. The distribution of IR AGNs is similar to that of X-ray AGNs, although they are typically found in somewhat less luminous galaxies, and show a less pronounced peak in the “green valley”.

$A = 0.1(u - r) + 0.08(M_{M_\odot} + 20)$
that there may be continuous feedback between star formation and accretion in these systems. While the precise nature of the AGN population associated with luminous starbursts is not yet clear, these studies point further towards important links between the growth of galaxies and their central SMBHs.

The future

Future X-ray surveys will provide more sensitive observations and larger AGN samples to study the characteristics and evolution of SMBH accretion in greater detail. One future prospect with Chandra is even deeper observations in the CDFs. Chandra’s high angular resolution will allow it to observe significantly deeper (up to 8 Ms or more) without reaching the confusion limit in the central regions (Alexander et al. 2003). This would allow the detection of a new population of extremely faint star-forming galaxies, as well as providing better photon statistics for the sources that have already been resolved. The upcoming NuSTAR \(^2\) mission (to launch 2011) will provide an unprecedented sensitive survey at hard X-ray (6–80 keV) energies, while the eROSITA \(^3\) instrument on the Spectrum X-Gamma observatory (also scheduled for 2011 launch) will survey the sky at 0.2–12 keV energies and will provide enormous samples of X-ray AGN. Among missions proposed for the future, Simbol-X \(^4\) (target launch 2014) would provide high angular resolution (better than 30") and high sensitivity in the ~0.5–80 keV range, while EXIST \(^5\) would conduct a large-area X-ray survey at very hard (5–600 keV) energies. The Wide-Field X-ray Telescope \(^6\) would provide an analog to SDSS in the X-ray band, detecting > 10\(^7\) X-ray AGN over > 10,000 deg\(^2\) in the energy range 0.1–4 keV (with the goal of reaching sensitivity to 6 keV). Further, the enormous sensitivity of the International X-ray Observatory \(^7\) would allow us to study in detail the spectra of large numbers of faint AGN. These future missions will be essential to build on our understanding of the growth of black holes and their place in the larger picture of galaxy and structure formation in the Universe.

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\(^2\)http://www.nustar.caltech.edu/. Correction: The original version of this article stated that NuSTAR will perform an all-sky survey; the mission will perform a series of smaller-area surveys.

\(^3\)http://www.mpe.mpg.de/projects.html#erosita

\(^4\)http://smsc.cnes.fr/SIMBOLX/

\(^5\)http://hea-www.harvard.edu/EXIST/

\(^6\)http://wfxt.pha.jhu.edu/

\(^7\)http://ixo.gsfc.nasa.gov/
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