New Astronomy Reviews 79 (2017) 59–84

Contents lists available at ScienceDirect

New Astronomy Reviews

journal homepage: www.elsevier.com/locate/newastrev

The *Chandra* deep fields: Lifting the veil on distant active galactic nuclei and X-ray emitting galaxies

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A R T I C L E I N F O

Article history:
Accepted 13 September 2017
Available online 18 September 2017

Keywords:
Black holes
Galaxies
Active galactic nuclei
Quasars
Accretion

A B S T R A C T

The *Chandra* Deep Fields (CDFs), being a major thrust among extragalactic X-ray surveys and complemented effectively by multiwavelength observations, have critically contributed to our dramatically improved characterization of the 0.5–8 keV cosmic X-ray background sources, the vast majority of which are distant active galactic nuclei (AGNs) and starburst and normal galaxies. In this review, I highlight some recent key observational results, mostly from the CDFs, on the AGN demography, the interactions between AGNs and their host galaxies, the evolution of non-active galaxy X-ray emission, and the census of X-ray galaxy groups and clusters through cosmic time, after providing the necessary background information. I then conclude by summarizing some significant open questions and discussing future prospects for moving forward.

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http://dx.doi.org/10.1016/j.newar.2017.09.002
1387-6473/

1. Introduction

1.1. Effectiveness of extragalactic X-ray surveys

Since the discovery of the cosmic X-ray background (CXRB; e.g., Giacconi, 1962), various major X-ray observatories have joined the efforts of resolving it into discrete cosmic sources as well as characterizing such sources, by carrying out different tiers of extragalactic X-ray surveys that range from shallow all-sky surveys to ultradeep pencil-beam surveys. Together, these surveys, being highly complementary to each other, effectively occupy the practically-accessible half of the so-called X-ray survey discovery space (i.e., X-ray flux limits achieved vs. solid angles covered; see Fig. 1),[1] powerfully providing a comprehensive understanding of X-ray source populations in the universe, and essentially reveal that the large portion ($\approx$80%) of the CXRB up to $\approx$10 keV can be accounted for by discrete X-ray point sources detected, among which the vast majority are accreting supermassive black holes (SMBHs; with millions to billions of solar masses), i.e., active galactic nuclei (AGNs), in addition to normal and starburst galaxies (see, e.g., Brandt and Hasinger, 2005 for a review).

X-ray AGN surveys are arguably the most effective method of identifying highly reliable and fairly complete samples of AGNs, due to several reasons (see, e.g., Section 1.1 of Brandt and Alexander (2015) for detailed reasoning and caveats): (1) Observationally, X-ray emission is nearly a universal feature of optically, infrared (IR), radio-selected AGNs that are neither highly Compton-thick (CT, i.e., with neutral hydrogen column densities of $N_{\rm H} \gtrsim 1.5 \times 10^{24}$ cm^{-2}; highly CT: $N_{\rm H} \gg 1.5 \times 10^{24}$ cm^{-2}; e.g., Lanzuisi (2015b)) nor intrinsically X-ray weak (such sources are very rare; see, e.g., Wu, 2011; Luo, 2014a). Theoretically, X-ray emission can be produced in various accretion disk models for AGNs that are applicable for a wide range of mass accretion rates (from sub-Eddington to super-Eddington accretion), disk temperatures (cold vs. hot accretion flows), gas opacities (optically thick vs. thin), and geometric structures (thin vs. thick); these models invoke a corona or corona-like component to Compton up-scatter soft photons into hard X-rays when necessary (see, e.g., Yuan and Narayan, 2014 for a review). (2) X-rays can penetrate through non-highly CT columns that are common among the majority AGN populations, and become even more penetrating at high redshifts due to positive K-correction, thereby reducing significantly absorption biases, probing immediate vicinities of SMBHs, and allowing for reliable $N_{\rm H}$ measurements to uncover intrinsic (i.e., absorption-corrected) AGN luminosities. (3) X-ray emission is subject to low dilution by host-galaxy stellar emission. An X-ray point source sitting right at the center of a galaxy is very likely to be an AGN; this serves as an effective way to identify distant AGNs when it is typically unfeasible to resolve spatially AGN light from host starlight. (4) An AGN X-ray spectrum is produced through numerous line and continuum emission processes subject to obscuration, and can therefore be utilized to infer physical conditions close to the SMBH, provided that the spectrum is of sufficient signal-to-noise ratio and energy resolution.

1.2. The *Chandra* deep fields

The *Chandra* Deep Fields (CDFs; see Fig. 2 and Table 1) consist of the *Chandra* Deep Field-South (CDF-S), the *Chandra* Deep Field-North (CDF-N), and the Extended-*Chandra* Deep Field-South (E-CDF-S). The CDF-S survey was originally led by R. Giacconi during 1999–2000 (1 Ms CDF-S; Giacconi, 2002), extended to 2 Ms

[1] Also see Fig. 3 and Table 3 of Brandt and Alexander (2015) for a recent demonstration and the information of additional X-ray surveys, respectively.

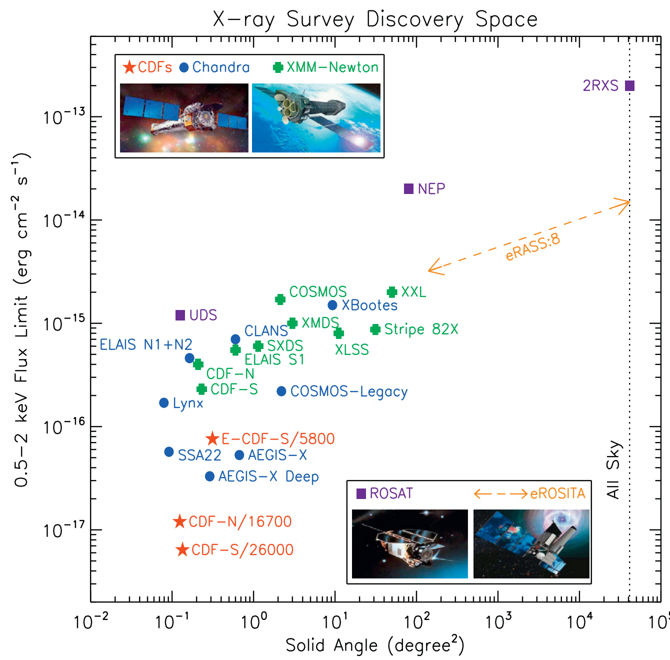

Fig. 1. Flux limits achieved versus solid angles covered by some selected X-ray surveys in the 0.5–2 keV band from *Chandra, XMM-Newton, ROSAT*, and *eROSITA*. The vertical dotted line indicates the solid angle for the whole sky. The surveys plotted are listed below, with their corresponding references shown in the parentheses: (1) for the *Chandra* Deep Fields (CDFs; red stars): the 7 Ms CDF-S survey (Luo, 2017), the 2 Ms CDF-N survey (Xue et al., 2016), and the 250 ks E-CDF-S survey (Xue et al., 2016), with the numbers annotated after the survey names indicating the observed X-ray source densities in their respective central 3-arcmin areas (these numbers have not been corrected for detection incompleteness or Eddington bias; see Table 1; cf. Section 2.1); (2) for the other *Chandra* surveys (blue bullets): the *Chandra* Deep Survey of the Extended Groth Strip (AEGIS-X; Laird, 2009), the AEGIS-X Deep survey (Nandra, 2015), the SSA22 protocluster survey (Lehmer, 2009), the Lynx survey (Stern, 2002), the *Chandra* COSMOS Legacy survey (Civano, 2016), the ELAIS N1+N2 deep X-ray survey (Manners, 2003), the *Chandra* Lockman Area North Survey (CLANS; Trouille et al., 2008), and the X-ray survey of the NDWFS Bootes field (XBootes; Murray, 2005); (3) for the *XMM-Newton* surveys (green crosses): the CDF-S survey (Ranalli, 2013), the CDF-N survey (Miyaji et al., 2003), the ELAIS-S1 field survey (Puccetti, 2006), the Subaru/*XMM-Newton* Deep Survey (SXDS; Ueda, 2008), the XMM-Large Scale Structure survey (XLSS; Chiappetti, 2013), the Stripe 82X survey (LaMassa, 2016), the XMM Medium Deep Survey (XMDS; Chiappetti, 2005), the COSMOS survey (Cappelluti, 2009), and the XXL survey (Pierre, 2017); (4) for the *ROSAT* surveys (purple squares): the *ROSAT* Ultra Deep Survey (UDS; Lehmann, 2001); the *ROSAT* North Ecliptic Pole survey (NEP; Henry et al., 2006), and the Second *ROSAT* all-sky survey source catalog (2RXS; Boller et al., 2016); and (5) the proposed final (4 years) *eROSITA* All-Sky Survey (eRASS:8; the orange dashed line with two arrow heads; (Merloni, 2012)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

through the Director's Discretionary Time (DDT) by the CXC director H. Tananbaum in 2007 (2 Ms CDF-S; Luo, 2008), awarded an additional 2 Ms DDT by H. Tananbaum in 2010 (4 Ms CDF-S; Xue, 2011), and eventually pushed to 7 Ms by W. N. Brandt during 2014–2016 (7 Ms CDF-S; Luo, 2017).[2] The CDF-S patch of sky, lying in the Fornax constellation, was chosen because of very low foreground Galactic $N_{\rm H}$ (8.8×10^{19} cm^{-2}; e.g., Stark, 1992), no bright ($m_{\rm V} \leq 14$) Galactic stars, and optimal visibility from large ground-based telescopes in Chile. The CDF-N project was initiated by G. Garmire (the first $\approx$0.5 Ms) and W. N. Brandt (the second $\approx$0.5 Ms) during 1999–2001 (1 Ms CDF-N; Brandt, 2001), and subsequently enlarged by W. N. Brandt during 2001–2002 (2 Ms

[2] In addition to the 7 Ms *Chandra* $\approx$0.3–8 keV CDF-S coverage, there are $\approx$3 Ms of CDF-S coverage with *XMM-Newton* at $\approx$0.2–12 keV (Comastri, 2011; Ranalli, 2013; see Fig. 1) and 200 ks of E-CDF-S coverage with *NuSTAR* at 3–24 keV (Mullaney, 2015a).