High-redshift AGNs and the next decade of Chandra and XMM-Newton

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We briefly review how X-ray observations of high-redshift active galactic nuclei (AGNs) at \( z = 4 – 7 \) have played a critical role in understanding their basic demographics as well as their physical processes; e.g., absorption by nuclear material and winds, accretion rates, and jet emission. We point out some key remaining areas of uncertainty, highlighting where further Chandra and XMM-Newton observations/analyses, combined with new multiwavelength survey data, can advance understanding over the next decade.

1 Introduction

Over the past \( \approx 17 \) yr, the observational capabilities of Chandra and XMM-Newton have allowed a large expansion, by more than an order of magnitude, in the number of X-ray detected active galactic nuclei (AGNs) at \( z = 4 – 7 \). This has come about via two primary routes. First, these missions have obtained follow-up observations in the X-ray regime of high-redshift AGNs previously found in other multiwavelength surveys [e.g., the Sloan Digital Sky Survey (SDSS), the Palomar Sky Survey (PSS), and the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) survey]. Second, these missions have discovered new X-ray selected high-redshift AGNs in their multiple X-ray surveys. According to a regularly updated public list compiled by Brandt & Vignali[1], there are now \( 153 \) X-ray detections of AGNs at \( z = 4 – 7 \), allowing reliable basic X-ray population studies into the reionization era. Most X-ray detections at \( z = 4 – 7 \) have come from the first route described above. However, new X-ray discoveries from the second route continue to advance rapidly, and these are extremely important because they mitigate many of the selection biases (e.g., due to obscuration and host-galaxy dilution) arising from optical/UV AGN selection.

In this paper, we will briefly review some of the insights that X-ray studies have provided about the first growing supermassive black holes (SMBHs) in the Universe. In §2 we will discuss X-ray surveys and AGN demographics, and then in §3 we will cover X-ray spectroscopy and AGN physics. For each of these topics, we will highlight areas of uncertainty and how these could be addressed in the next decade with Chandra and XMM-Newton observations/analyses.

Owing to space limitations, complex details will often need to be suppressed and citations cannot be complete but just representative. Please check the cited papers and relevant recent reviews (e.g., Brandt & Alexander 2015; Reines & Comastri 2016) for further references.

2 X-ray surveys and high-redshift AGN demographics

2.1 Current results

In contrast to early suggestions from ROSAT surveys, current surveys with Chandra and XMM-Newton clearly find an exponential decline in the space density of luminous AGNs at \( z > 3 \) (e.g., see Fig. 1). The decline is often modeled as \( \Phi(z) \propto (1 + z)^p \text{Mpc}^{-3} \) with \( p \approx -6.0 \). Space-density comparisons between luminous X-ray selected AGNs and optically selected quasars indicate agreement to within factors of \( 2–3 \) (e.g., McGregor et al. 2013; Marchesi et al. 2016).

At lower luminosities of \( L_X \approx 10^{43} – 10^{44} \) erg s\(^{-1} \) (for the 2–10 keV band), the space-density evolution is quantitatively less clear at high redshifts owing to a number of factors: small sample sizes, follow-up and completeness challenges, and sensitivity of the results to analysis details. However, at least qualitatively all the latest results support a decline in space density at \( z > 3 \) also for these objects. For example, Vito et al. (2014) find that the rate of decline in space density is plausibly consistent with that at higher luminosities, while Georgakakis et al. (2015) suggest the

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1 http://www2.astro.psu.edu/users/niel/papers/highz-xray-detected.txt
Fig. 1  X-ray selected AGN space density in three color-coded bins of 2–10 keV luminosity, derived using a selection of X-ray surveys that sample the luminosity-redshift plane. The lighter colors are for a pure density evolution model, and the darker colors are for a luminosity dependent density evolution model. The gridded parts of the green stripes indicate a region where the space density is highly uncertain. Note the decline in space density with redshift for all three luminosity bins. Adapted from Vito et al. (2014), where the correction for redshift incompleteness is described.

Fig. 2 (Top) Stacked 0.5–2 keV Chandra CDF-S images for samples of (individually X-ray undetected) high-redshift galaxies. Dashed circles are centered at the positions of the stacked galaxies with radii corresponding to the median extraction radius used for the relevant sources. The upper panels show results for all available galaxies in the listed redshift ranges, while the lower panels show only the most-massive half of the galaxy samples. Stacked X-ray detections are obtained at $z = 3.5–4.5$ and $z = 4.5–5.5$ (the detection significance levels are listed), while tight upper limits are obtained for $z = 5.5–6.5$ and higher redshifts. Each panel also lists the corresponding total stacked exposure time, ranging from 21–260 yr. Adapted from Vito et al. (2016). (Bottom) Constraints on the SMBH accretion-rate density vs. redshift derived from the stacking results for all galaxies (black points and upper limits) and for the most massive half (red points and upper limits). Gray points show the (dominant) contribution from X-ray detected AGNs in the CDF-S. The findings are compared with a selection of $z = 0–5$ observational results. The data demonstrate that most high-redshift SMBH growth occurs in the short AGN phase; any continuous low-rate accretion contribution appears small. Adapted from Vito et al. (2016), where many further details are provided.

It is also critical to constrain the amount of high-redshift SMBH growth that may be occurring at still lower luminosities, corresponding to fluxes below the detection limits of even the deepest current X-ray surveys. Such SMBH growth could occur, e.g., in a continuous or near-continuous low-rate mode, in contrast to the shorter high-rate mode associated with individually X-ray detected AGNs. This type of SMBH growth can be usefully constrained with X-ray stacking studies, where the X-ray emission from hundreds of individually undetected galaxies is co-added. Fig. 2 shows some current results derived from the deepest X-ray survey to date, the 7 Ms Chandra exposure of the Chandra Deep Field-South (CDF-S; Luo et al. 2016), where stacked detections are achieved up to $z = 4.5–5.5$ and tight upper limits are set at still higher redshifts. Each galaxy sample stacked in Fig. 2 contains 100–1300 galaxies, and impressively large stacked exposure times of 21–260 yr are reached. The detected X-ray signals are plausibly consistent with expectations for high-redshift X-ray binary populations, according to the latest constraints on these populations at lower redshifts by Fragos et al. (2013) and Lehmer et al. (2016). Thus, there is no detected evidence for SMBH growth in a continuous low-rate mode, and the quantitative constraints indicate this mode is not significant at least out to $z \approx 6$ (see the bottom panel of Fig. 2).
Collectively, the combined demographic constraints from individual X-ray detections and stacking indicate that AGNs are unlikely to drive reionization at \( z \approx 6 \), leaving stars as the most-likely culprit (e.g., Georgakakis et al. 2015; Vito et al. 2016). AGNs may, however, play a secondary role in distributed heating of the intergalactic medium (e.g., Grissom et al. 2014).

### 2.2 Massive X-ray archive mining enabled by new very wide field surveys

Fig. 2 is helpful to review when considering X-ray survey prospects for the next decade of Chandra and XMM-Newton. It shows that there will be a flood of very wide field multiwavelength photometric data and optical/near-infrared spectroscopic data becoming available. While some of these projects have “first light” dates well into the future that are thus necessarily uncertain, others are more definite. For example, the Large Synoptic Survey Telescope (LSST) is now under active construction, and its deep-wide \( ugrizy \) main survey should discover \( \approx 20 \) million AGNs including many from \( z = 4–7.5 \). Combining LSST data with data from Euclid and WFIRST (see the bottom panel of Fig. 3), it should be possible to discover many more AGNs including \( \geq 1000 \) at \( z > 7 \) and \( \geq 20 \) at \( z > 10 \) (e.g., Spergel et al. 2013). Thus, over the next decade, the demographic details of the unobscured and moderately obscured AGN population should become well understood out to very high redshifts.

X-ray studies can vitally complement this work by revealing the demographics of highly obscured AGNs out to high redshifts, and one can imagine extremely powerful high-redshift investigations that combine thousands of archival Chandra and XMM-Newton observations with the sensitive and very wide field imaging from, e.g., the Dark Energy Survey (DES), Hyper Suprime-Cam (HSC), LSST, Euclid, and WFIRST (see Fig. 3). Hopefully, eROSITA will also contribute key X-ray data to this endeavor. In these investigations, AGNs detected in the archival X-ray data would be identified as high-redshift candidates based on their superb optical/infrared photometric data using primarily the Ly\( \alpha \) forest (see the bottom panel of Fig. 3). The only new observational cost would be to perform optical/near-infrared spectroscopic follow-up of these candidates. Such follow-up could be partly obtained with next-generation wide-field spectroscopic surveys; e.g., the Dark Energy Spectroscopic Instrument (DESI) and the Prime Focus Spectrograph (PFS) of Subaru Measurement of Images and Redshifts (SuMIRe) as shown in Fig. 3. For the optically fainter AGNs, dedicated spectroscopy with future Extremely Large Telescopes could be obtained.

In 2025, one could plausibly aim to perform such a survey over \( \approx 1200 \deg^2 \) utilizing the deepest \( \approx 60\% \) of Chandra and XMM-Newton archival observations (see Fig. 4). These would mostly be 20–100 ks exposures, but with a few exposures up to Ms levels. Such a massive archival survey, using \( \approx 25 \) yr of data from both Chandra and XMM-Newton, should detect 500–1100 AGNs at \( z = 4–6 \) and 100–1000 at \( z = 6–8 \), considering both obscured and unobscured systems. The detected AGNs will be relatively luminous with 2–10 keV luminosities of \( L_X = 10^{43.5} \) erg s\(^{-1} \) at \( z = 4–6 \) and \( L_X = 10^{44.5} \) erg s\(^{-1} \) at \( z = 6–8 \). The quoted luminosity ranges cover \( \approx 90\% \) of the expected detections, providing quality constraints on the X-ray luminosity function and the X-ray obscured fraction \( f_{\text{obsc}} \) in this regime. \( f_{\text{obsc}} \) may have a non-monotonic and physically informative dependence upon luminosity. In contrast to the general \( f_{\text{obsc}}-L_X \) anticorrelation observed at lower AGN luminosities, the latest results from wide-field infrared surveys (e.g., Assef et al. 2015) indicate the fraction of highly obscured AGNs rises upward to \( \approx 50\% \) at the highest AGN luminosities. This may be due to two different types of X-ray obscuration needing further investigation. At lower AGN luminosities of \( L_X < 10^{44} \) erg s\(^{-1} \), setting detailed constraints on the \( z = 4–8 \) X-ray luminosity function will require deeper X-ray observations over large areas with, e.g., Athena and X-ray Surveyor.

The massive archival survey described above, by dint of its large solid-angle coverage, will automatically sample a wide range of high-redshift cosmic environments. However, even it will tend to undersample rare regions such as the most overdense structures in the early universe, where simulations predict that high-rate SMBH accretion can be sustained by protogalaxy merger episodes or continuous accretion of cold gas (e.g., Li et al. 2007; Di Matteo et al. 2012; Costa et al. 2014). The sampling of such regions can be improved via targeted deep Chandra and XMM-Newton observations. One such Chandra program is ongoing to determine the AGN content in the overdensity around the \( z = 6.28 \) quasar SDSS J1030+0524, and additional impressive overdensities at \( z > 4 \) will surely be identified by the wide-field surveys shown in Fig. 3.

### 2.3 X-ray stacking of JWST galaxy samples

The next decade will also bring substantially improved X-ray stacking studies that constrain further the average amount of SMBH accretion out to the highest redshifts. These will combine the deepest X-ray surveys with, e.g., high-redshift galaxy samples found in JWST observations.

The extremely deep photometric and spectroscopic data provided by JWST will greatly improve the quality of the galaxy samples being stacked, allowing better redshift identifications and improved removal of low-redshift interlopers. Even more importantly, the redshift range of the galaxy samples will be extended up to \( z \approx 15 \) with good source statistics (compare with Fig. 2), breaking into the critical redshift range where stacking constraints on the faint end of the X-ray luminosity function will directly probe SMBH seeding mechanisms.
et al. 2016). Such stacking investigations will lay critical groundwork for X-ray Surveyor.

3 X-ray spectroscopy and high-redshift AGN physics

3.1 Obscured protoquasars and host-galaxy feedback

A commonly considered picture for the formation of the first SMBHs at high redshifts involves the growth via accretion of lower mass black-hole seeds in gas-rich and frequently merging protogalaxies (e.g., Li et al. 2007). As these seeds grow into SMBHs, their moderate-luminosity emission is initially obscured (“obscured protoquasars”) until one of the SMBHs grows to a mass where it can provide effective feedback, likely via a radiation-driven wind. At this point, cold gas is expelled from the host galaxy by the wind, revealing a luminous unobscured AGN. Eventually, the feedback may expel sufficient gas to limit further SMBH growth and host-galaxy star formation.

X-ray spectroscopic investigations can provide insights into and constraints upon this picture. First, X-ray spectroscopic studies of moderate-luminosity $z = 3–5$ AGNs in the deepest X-ray surveys commonly ($\gtrsim 50\%$) show heavy obscuration with $N_{\text{H}} > 10^{23}$ cm$^{-2}$ (see Fig. 5), consistent with expectations for obscured protoquasars. Additional deep surveys with Chandra and XMM-Newton, obtaining sufficient photon statistics for robust source spectral characterization, can improve constraints upon this fraction at $z = 3–5$ and its luminosity dependence.

Furthermore, as observed at lower redshift, some luminous high-redshift quasars have shown relativistic outflows revealed primarily via iron K absorption lines. These outflows likely possess sufficient mass-outflow rates and kinetic powers to expel large masses of cold gas from host galaxies, as needed in the picture above. The prototypical example of such a system is the gravitationally lensed quasar APM 08279+5255 at $z = 3.91$, where a relativistic wind with velocities of $0.1–0.4c$, or larger, is detected (Chartas et al. 2002, 2009). Modeling suggests a mass-outflow rate of $10–60 M_{\odot}$ yr$^{-1}$ and a kinetic luminosity of $\approx 10^{46}$ erg s$^{-1}$. Such outflows could be present, but undetected, in many other high-redshift quasars—for APM 08279+5255, the lensing provides uniquely high X-ray spectral quality. Deep X-ray spectroscopy of a few additional carefully selected quasars at $z \approx 4–6$ could search for similar wind-feedback signatures.

3.2 Measuring early SMBH accretion

The very observation of $10^8–10^{10} M_{\odot}$ SMBHs in quasars at $z = 4–7$, less than 1–2 Gyr after the Big Bang, sets tight constraints on models for the formation and growth of early SMBHs. In order to explain the large SMBH masses observed up to $z = 6–7$, one would need almost uninterrupted, Eddington-limited, accretion of gas from $z \approx 20$ to $z \approx 6$ with fairly low radiative efficiency. Given the challenge arising from the first quasars, it is of natural interest to determine the accretion properties of high-redshift AGNs, searching for, e.g., Eddington-limited accretion.

X-ray observations can provide unique insights about the inner accretion disk and its corona out to high redshift. For example, the ratio between the X-ray and optical/UV luminosities measures the relative importance of the accretion-disk corona vs. the disk itself (see §4 of Brandt & Alexander 2015 for a recent review). This ratio is usually parameterized by $\alpha_{\text{ox}}$ which is the slope of a nominal power law joining rest-frame 2500 Å and 2 keV [i.e., $\alpha_{\text{ox}} = 0.38 \log(L_{2 \text{keV}}/L_{2500 \text{Å}})$]. A significant correlation between $\alpha_{\text{ox}}$ and the UV luminosity ($L_{2500 \text{Å}}$) has been known since early studies, and this correlation has now been measured precisely with large samples of optically (e.g., Steffen et al. 2006; Just et al. 2007) and X-ray (e.g., Lusso et al. 2010) selected AGNs. Luminous quasars have spectral energy distributions (SEDs) with steeper (i.e., more negative) $\alpha_{\text{ox}}$ indices indicating the dominance of the disk emission with respect to the X-ray luminosity produced in the corona. It is thus common also to utilize $\Delta \alpha_{\text{ox}} = \alpha_{\text{ox}}(\text{Observed}) - \alpha_{\text{ox}}(L_{2500 \text{Å}})$, which usefully quantifies the observed X-ray luminosity relative to that expected from the $\alpha_{\text{ox}}-L_{2500 \text{Å}}$ relation. Most recent studies find no significant evolution of $\alpha_{\text{ox}}$ or $\Delta \alpha_{\text{ox}}$ with redshift out to $z \approx 5–6$, beyond which the source statistics become too limited for robust constraints (e.g., Just et al. 2007; Lusso et al. 2010; but see Kelly et al. 2007). The tightest limits upon the $\alpha_{\text{ox}}-z$ relation imply that variations of the typical $L_{\text{X}}/L_{\text{UV}}$ ratio with redshift are less than 30%. This lack of strong $\alpha_{\text{ox}}$ and $\Delta \alpha_{\text{ox}}$ evolution is broadly consistent with the similar lack of evolution in other quasar properties generally: e.g., infrared continuum emission (e.g., Jiang et al. 2006, 2010), emission-line strengths (e.g., De Rosa et al. 2011; Fan 2012), and X-ray variability (e.g., Yang et al. 2016).

The photon index of the hard X-ray power-law continuum ($\Gamma$), which also measures the coupling between disk emission and the overlying hot corona, seems empirically to be a more robust tracer of the accretion rate than $\alpha_{\text{ox}}$. After the pioneering work of Shemmer et al. (2006), the relation between $\Gamma$ and the Eddington ratio ($\lambda_{\text{Edd}} = L/\dot{L}_{\text{Edd}}$) has been established over a range of redshifts for sizable samples of sources; steeper slopes correspond to higher implied $\lambda_{\text{Edd}}$ (e.g., Shemmer et al. 2008; Risaliti et al. 2009; Brightman et al. 2013; Fanali et al. 2013). The current studies of $z \approx 4–5.5$ radio-quiet quasars generally do not indicate exceptional $\Gamma$ or $\lambda_{\text{Edd}}$ values (e.g., Shemmer et al. 2005; Vignali et al. 2005). However, there are hints of potentially steep $\Gamma$ values for two quasars at $z = 6.28$ and $z = 7.08$, one of which is debated (Farrah et al. 2004; Moretti et al. 2014 vs. Page et al. 2014).

All current X-ray spectral studies of $z > 4$ quasars suffer from limited photon statistics, and major observational investments with Chandra and XMM-Newton could improve this situation allowing more general and reliable...
conclusions about X-ray continuum shapes to be drawn. This is especially true at the highest redshifts of $z > 6$. As high-redshift quasars are faint and thus subject to significant damage when satellite background flaring occurs, any further flaring accommodations would be helpful to ensure that such approved observations actually achieve their full proposed exposures. In the more distant future, as luminous quasars at $z = 7-10$ are discovered by the combination of DES, HSC, LSST, Euclid, and WFIRST (see §2.2 for details), these will be critical targets for pushing X-ray spectral constraints deep into the reionization era.

3.3 Extreme AGN sub-populations at high redshift

Extreme AGN sub-populations can often ultimately be used as tools to teach us about the broader population more generally. Such extreme objects can reveal accretion phenomena that are generally applicable but are difficult to identify when more subtly expressed in the overall population. There are several extreme AGN sub-populations that have been identified at $z > 4$ (and often also at lower redshifts), including weak-line quasars (e.g., Diamond-Stanic et al. 2009; Luo et al. 2015), hot-dust poor quasars (e.g., Jiang et al. 2006, 2010), and highly radio-loud quasars (e.g., Wu et al. 2013; Ghisellini et al. 2015), and X-ray studies of these can provide insights about their nature.

X-ray observations of a large sample of weak-line quasars support a model where these quasars possess thick inner accretion disks, perhaps due to high $\lambda_{\text{Edd}}$ (Luo et al. 2015). This model can explain, in a simple and unified manner, their weak lines and diverse X-ray properties. Further X-ray spectroscopy of selected weak-line quasars can search for spectral signatures associated with the thick inner disk. Finally, highly radio-loud quasars at $z > 4$ (including some blazars), which launch the most-powerful jets made by growing SMBHs in the early universe, appear $\approx 3$ times X-ray brighter than their matched counterparts at lower redshifts (Wu et al. 2013). This may be due to a fractional IC/CMB contribution (inverse Compton scattering of the cosmic microwave background) to the jet-linked core X-ray luminosity that grows rapidly with redshift. Further Chandra and XMM-Newton observations/analyses can establish definitively these high-redshift X-ray enhancements and clarify their dependence upon redshift, allowing testing of the fractional IC/CMB model.

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Fig. 3  (Top) Gantt chart showing expected operation dates for some selected future large survey projects. Dates are approximate and become increasingly uncertain further into the future. Some listed projects will likely extend beyond 2030. For comparison, the next decade of XMM-Newton corresponds to 2016–2026. (Bottom) Expected depths for the LSST (10 yr), Euclid, and WFIRST surveys. Labels above each bar show photometric bands, and labels below each bar show the PSF 50% encircled-energy radius in units of 0.01 arcsec. The orange arrows near the bottom of the panel show the location of Lyα at z = 7 and z = 10. Note the generally good match between LSST and WFIRST depths. Adapted from Spergel et al. (2013), where many further details are provided.

Fig. 4  Approximate solid-angle vs. depth plot for a massive 25 yr archival Chandra and XMM-Newton survey that could be performed in 2025. This has been derived by scaling from the currently available archival data, assuming that the future distributions of exposure times remain similar to the past ones. Only the deepest 60% of Chandra and XMM-Newton archival observations are considered; these are mostly 20–100 ks exposures, but with a few exposures up to Ms levels. We have randomly removed 1/3 of all observations to account for those not suitable for extragalactic surveys work (e.g., pointings in the Galactic plane, of bright and extended foreground galaxies, or of bright foreground galaxy clusters). We have also approximately accounted for the expected sensitivity loss over time of Chandra and XMM-Newton.
Fig. 5  (Top) Observed-frame radio-to-X-ray SED of a spectroscopically confirmed Compton-thick AGN at $z = 4.76$ in the CDF-S. The SED has been decomposed into an AGN component (blue dotted line) and a starburst-galaxy component (red dashed line); the green solid line is the sum of the two. Adapted from Gilli et al. (2011). (Bottom) Best-fitting column density vs. redshift for high-redshift CDF-S AGNs (upper limits are shown as downward pointing arrows). More than half of these X-ray selected AGNs are highly obscured with $N_H > 10^{23}$ cm$^{-2}$. Adapted from Vito et al. (2013, 2014).