X-ray imaging and spectroscopy of (radio-quiet) AGN: highlights from Chandra and XMM-Newton

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Abstract

The X-ray observatories XMM-Newton and Chandra provided a wealth of exciting new results. Chandra delivered X-ray images of outstanding detail, reaching subarcsecond spatial resolution for the first time in X-ray astronomy. XMM-Newton provided the highest-signal X-ray spectra ever taken. The imaging and spectral observations are greatly improving our understanding of the physical processes in the central region of active galaxies. The increased sensitivity also allows to peer into the high-redshift universe beyond \( z=5 \).

I shall provide a review of recent X-ray highlights on (radio-quiet) AGN from low to high redshift, and exciting questions still open. I conclude with a glimpse into the future of X-ray astronomy.

1 Introduction

1.1 X-ray probes of the black hole region of AGN

X-ray emission originates from the immediate vicinity of the black hole. The detection of luminous, hard, power-law-like X-ray emission, rapid variability, and the recent discovery of relativistic effects in the iron-K line profile provided excellent evidence for the presence of supermassive black holes (SMBHs) in active galaxies. X-ray observations currently constitute the most powerful means to explore the black hole region of AGN.

X-rays at the centers of AGN arise in the accretion-disk – corona system. On larger scales, but still within the central region, X-rays might be emitted by a hot intercloud medium at distances of the broad or narrow-line region. The X-rays which originate from the accretion-disk region are reprocessed in form of absorption and partial re-emission (e.g., George & Fabian 1991, Netzer 1993, Krolik & Kriss 1995, Collin-Souffrin et al. 1996, Komossa & Fink 1997) as they make their way out of the nucleus. The reprocessing bears the disadvantage of veiling the intrinsic X-ray spectral shape, and the spectral disentanglement of many different potentially contributing components is not always easy. However, reprocessing also offers the unique chance to study the physical conditions and dynamical states of the reprocessing material, including the outer parts of the accretion disk; the ionized absorber; the torus, which plays an important role in AGN unification schemes (Antonucci 1993); and the BLR and NLR. Detailed modeling of the reprocessor(s) is also indispensable to recover the shape and properties of the intrinsic X-ray spectrum.
1.2 Chandra and XMM-Newton

There are two key abilities of the new X-ray observatories XMM-Newton (e.g., Jansen et al. 2001) and Chandra (e.g., Tananbaum & Weisskopf 2001, Weisskopf et al. 2002). One is the superb spatial resolution of Chandra, providing images rich in details on the 1 arcsec-level for the first time. The other is the increase in spectral resolution of XMM and Chandra, providing X-ray spectra with such a wealth of features including many narrow absorption and emission lines, detected in X-rays for the first time.

Both missions have imaging detectors (energy bandpass ∼(0.1–10) keV) and grating spectrometers aboard. Below, a short review of results from these observatories is given. Due to space limitations it will necessarily be incomplete, both in topics covered and in citations given. My apologies in advance.

2 X-ray imaging spectroscopy of AGN

2.1 Nearby Seyfert galaxies

Among the first published AGN X-ray images taken with Chandra was that of NGC 1068 (Young et al. 2001). The image demonstrated the outstanding spatial resolution power of the X-ray observatory. While it had been noted before that the X-ray emission of NGC 1068 was extended, with Chandra for the first time a wealth of details was seen. One could actually immediately realize one was looking at a galaxy just by inspecting the X-ray image (Fig. 1). The following details could be recognized (Young et al. 2001): a bright compact core (165 pc), emission extending to the north-east coincident with the NLR, and large-scale emission partly tracing the spiral arms. Similarly spectacular is the X-ray spectrum of NGC 1068, addressed below (Sect. 3.1).

The nearby Seyfert galaxy NGC 4151 is among the best studied AGN across the electromagnetic spectrum. Again, its extended X-ray emission was noted previously (e.g., Elvis et al. 1983). Details remained unknown, though. Chandra resolved the extended emission (Ogle et al. 2000), showed that it is spatially coincident with the NLR and of high temperature.

2.2 Ultra-luminous infrared galaxies

Ultra-luminous infrared galaxies (ULIRGs) are characterized by their huge luminosity output in the infrared, powered by central starburst and/or AGN activity. X-rays provide an excellent tool to search for deeply obscured AGN at the centers of ULIRGs, and also allow to trace starburst-superwind activity. With Chandra, the ULIRGs Mrk 273 (Xia et al. 2002), Mrk 231 (Gallagher et al. 2002b) and Arp 220 (Clements et al. 2002) were resolved in X-rays, revealing many details. Since there is a separate review on ULIRGs (Xia, these proceedings), the rest of this section will concentrate on NGC 6240, a recent Chandra observation of which revealed some surprises: Despite decades of searches and debates whether an AGN is present at all in this source (for an overview see Sect. 2 of Komossa & Schulz 1999), a clear detection remained elusive prior to the registration of hard X-ray emission beyond 2-10 keV with ROSAT, ASCA, and particularly BeppoSAX and RXTE. Both, Beppo-Sax and RXTE did not posses spatial resolution across the field of view, but the most likely counterpart of the hard X-ray emission was argued to be NGC 6240. The unprecedented spatial resolution of Chandra, coupled with simultaneous energy information, let to the detection of luminous, hard X-ray emission and strong neutral iron lines from both cores of the galaxy (Fig. 1.2). These properties are the characteristic features of the presence...
of AGN, implying both cores of NGC 6240 are active (Komossa et al. 2003). The two supermassive black holes are presently separated by $\sim 3000$ ly. The final merging of these black holes is expected to produce a strong gravitational wave signal of the kind detectable with the future space-borne observatory LISA (e.g., Danzmann 1996, Centrella 2003).

In addition to the double black hole, NGC 6240 exhibits luminous extended X-ray emission, first detected with the instruments aboard ROSAT (e.g., Schulz et al. 1998), and spatially and spectroscopically resolved with Chandra (Komossa et al. 2003). It is very likely related to starburst-superwind activity and changes its rich structure in dependence of energy. While the more extended starburst loops have a lower X-ray temperature, there is also a more compact component surrounding the two nuclei which is of higher temperature and shows a tendency for higher metal abundances than the more extended component.

Chandra observations of more ULIRGs are expected to provide a sharp and detailed look at the very centers of these galaxies in the coming years.
3 High-resolution X-ray spectroscopy of AGN

For the first time, high-resolution spectroscopy of AGN can be performed in X-rays. With the exception of a few high-quality ASCA spectra of nearby AGN, the number of X-ray features typically seen in AGN spectra was 2-3. This strongly increased now; typically \( \sim 20-30 \) features are detected in the spectra of nearby AGN and even more in the brightest, best-studied objects. A special role is played by warm absorbers. Recognized earlier (see Komossa 1999 for a pre-Chandra review), they have now become the most important X-ray diagnostic of the central region of AGN, imprinting many absorption lines on soft X-ray spectra of Seyfert 1 galaxies. There have even been suggestions that the emission-lines detected in nearby Seyfert 2 galaxies are also related to ionized absorbers, seen from the side.

Basically, the trend emerged that Seyfert 1 X-ray spectra are dominated by absorption, while Seyfert 2 X-ray spectra are dominated by emission-lines. There are some exceptions, like NGC 4151, a classical Seyfert 1 galaxy of type 1.5 (e.g., Osterbrock & Koski 1976), which in X-rays looks more like a Seyfert 2 (e.g., Kahn et al. 2001). Only very few AGN X-ray spectra turned out to be completely featureless (e.g., Marshall et al. 2002).

3.1 Seyfert 2 galaxies: emission-line spectroscopy

I would like to start, again, with NGC 1068. Both, Chandra and XMM-Newton had a deep look at this galaxy (e.g., Kahn et al. 2001, Kinkhabwala et al. 2002, Brinkman et al. 2002). Its soft X-ray spectrum is extremely rich in emission lines and is dominated by H-like and He-like ions of low Z, and by Fe-L shell ions (Fig. 3). Kinkhabwala et al. (2002) inferred that the emission-line spectrum is photoionized by the nuclear continuum, and pointed out that the inferred column densities of the ions in the X-ray gas match those derived for warm absorbers detected by absorption-spectroscopy of Seyfert 1 galaxies. The relatively cold X-ray gas spatially coincides with the optical ionization cones of NGC 1068. The inferred broad distribution of ionization parameters necessary to explain the X-ray spectrum, requires the presence of a distribution of densities (several orders of magnitude) at each radius in the ionization cone (Brinkman et al. 2002, Kinkhabwala et al. 2002). It is interesting to note, that photoionization modelling of the optical radiation cone spectrum of NGC 4151 (Schulz et al. 1993) and of the optical spectra of Seyfert 2 galaxies (Komossa & Schulz 1997) reached the same conclusion (i.e., the requirement of a range in densities at fixed radius in order to reproduce the observed emission lines).

While most attention now is focussed on employing the new observatories in orbit, a number of surprises and exciting results may still linger in the archives of ROSAT, ASCA and BeppoSAX data. Making use of archival RXTE, BeppoSAX and ASCA data, Colbert et al. (2002) reported the detection of a flare in the 6.7 keV FeK emission-line of NGC 1068. The line is interpreted as arising in warm reflecting material in the center (< 0.2 pc from the AGN core) of the galaxy.

The X-ray emission lines detected in the spectra of several more Seyfert 2 galaxies (e.g., Mrk 3 and the Circinus galaxy) and in NGC 4151, contain important information on the physical conditions in the line-emitting medium, like temperature, density, and the main gas excitation/ionization mechanism; photoionization or collisional ionization. Of particular importance in determining the main power mechanism of the lines are the Helium-like triplets, the widths of the radiative recombination continua, and the strengths of the Fe-L complexes.

The emission lines in the X-ray spectrum of NGC 4151 (Ogle et al. 2000) are narrow and exhibit properties characteristic for the narrow-line region. This is the first X-ray NLR
The general trend emerged, that the extended gas in Seyfert 2 galaxies appears to be photoionized out to relatively large distances from the nucleus.

3.2 Seyfert 1 galaxies: absorption spectroscopy

Neutral (‘cold’) or ionized (‘warm’) gaseous material is ubiquitous in the AGN/SMBH environment, and therefore of utmost importance in understanding the AGN phenomenon, the evolution of active galaxies, their link with starburst galaxies and ULIRGs, and the X-ray background. X-ray absorption and emission features provide valuable diagnostics of the physical conditions in the X-ray gas.

Chandra spectroscopy of NGC 5548, performed with the Low Energy Transmission Grating Spectrometer, LETGS, revealed for the first time a system of deep narrow absorption lines in the X-ray spectrum of an AGN (Kaastra et al. 2000, 2002). These lines arise from ionized material in the nucleus of NGC 5548 and show a range of ionization states.

While all AGN in deep fields are exposed for megaseconds, the record for the deepest grating observation of a nearby galaxy is held by NGC 3783. The warm absorber of this source was discovered in pioneering work by Turner et al. (1993). The 900ks Chandra spectrum (e.g., Fig. 1 of Kaspi et al. 2002) exhibits a wealth of absorption (and emission) features.

1Ultimately, the goal will be to combine IR, optical, UV and X-ray observations in a renewed attempt to finally derive the parameters the NLR of NGC 4151 and to infer the unobserved EUV-SED of this galaxy; many attempts were done during the last decade, demonstrating that several different solutions exist (e.g., Contini et al. 2002 and ref. therein).
Using *Chandra* and *XMM-Newton*, absorption-complexes were detected and studied in several more AGN, including IRAS 13349+2438 (Sako et al. 2001), NGC 4051 (Collinge et al. 2001), NGC 3227 (Komossa et al. 2001), MCG –6-30-15 (Branduardi-Raymont et al. 2001, Lee et al. 2001), Mrk 509 (Yaqoob et al. 2002), NGC 4593 (Steenbrugge et al. 2002), Ark 564 (Marshall 2002, Matsumoto et al. 2002) and NGC 3516 (Netzer et al. 2002). Generally, the trend emerges that the warm absorbers are complex multi-component structures with a range in ionization parameters.

The detailed atomic physics involved in producing the X-ray spectra of Seyfert galaxies, and the consequences for our understanding of the central region of AGN, are still under scrutiny. The X-ray spectra of the brightest AGN are so rich, that it will take a while until all available information is extracted from them.

### 3.3 Iron lines

The iron lines beyond 6 keV are the most important diagnostics at these energies (see Fabian 2001, O’Brien et al. 2003 for reviews). If the line is formed in the inner parts of the accretion-disk, its profile reflects the general relativistic effect of gravitational redshift and the special relativistic effects of beaming and transverse Doppler effect. The best-studied iron-line case is MCG –6-30-15. At certain times, the red wing of MCG–6-30-15 is very broad, extending down to very soft energies (Wilms et al. 2001).

*Chandra* and *XMM* confirmed and further corroborated that the iron line profiles are complex and that many components of the active nucleus may contribute to iron-line emission, including likely the BLR (NGC 5548), the torus (NGC 3783, Mrk 205), the X-ray ionization cone of NGC 1068, and a contribution from the outer parts of the accretion disk (MCG–6-30-15). A particularly interesting case is the iron-line complex of NGC 3516. Turner et al. (2002) reported the presence of several narrow components within the FeKα profile of this galaxy. Their origin is still somewhat unclear. More details on the iron-line topic are given in the contributions by J. Wilms and T. Wang (these proceedings).

### 4 (Distant) quasars

#### 4.1 BAL quasars

Broad absorption line (BAL) quasars are characterized by broad UV absorption lines. It has been suggested that these lines arise in a flow of gas which rises vertically from a narrow range of radii from the accretion disk. The flow then bends and forms a conical wind moving radially outwards (Elvis 2000). Variants of radiatively-driven disk-winds were explored (e.g., Murray et al. 1995, Proga et al. 2000, Proga 2001, Everett et al. 2002). In some of these models, an X-ray absorber shields the wind downstream from soft X-rays, allowing resonant-line driving to remain effective and accelerate the outflowing BAL wind up to \( \sim 0.1c \).

Pre-*Chandra*/XMM detections of BAL quasars in X-rays were rare. Generally, BAL quasars are X-ray weak, which is usually interpreted in terms of strong excess absorption (e.g., Green et al. 1995, Gallagher et al. 1999, Brinkmann et al. 1999, Brandt et al. 2000, Wang et al. 2000). *Chandra* provided valuable new constraints on the amount of absorption towards selected BALs (e.g., Sabra & Hamann 2001, Oshima et al. 2001, Gallagher et al. 2002, Sabra et al. 2002), and an XMM observation let to a new identification of the X-ray counterpart of the BAL quasar PHL 5200 (Brinkmann et al. 2002). Almost all data still suffer from low S/N (typically 50 to few hundred detected X-ray photons), though. There
Figure 4: XMM-Newton spectrum of the BAL quasar APM 08279+5255 at redshift $z=3.91$ (Hasinger et al. 2002). Left: XMM EPIC-pn spectrum, fit with a single powerlaw. An absorption feature is visible at an energy corresponding to ionized, redshifted iron. Right: Combined EPIC and MOS spectra, fit with a powerlaw plus an absorption edge of highly ionized iron.

are indications that the BAL material is ionized instead of neutral. This is definitely the case for the quasar APM 08279+5255 which has the best-measured X-ray spectrum of any BAL quasar I am aware of. APM 08279+5255 is magnified by a gravitational lens and is among the most luminous objects in the universe (even after correction for lensing). A 100ks XMM-Newton observation (Fig. 4) led to the detection of a strong absorption feature of ionized iron, interpreted as K-edges, arising from a warm absorber of high column density (Hasinger et al. 2002). A recent Chandra spectrum shows similar, but not identical features, in the sense that the high-energy dip in the spectrum is interpreted-modeled in terms of two highly blueshifted (in the quasar rest frame) iron-lines rather than edges (Chartas et al. 2002). Combining the available observations, variability in the BAL-flow is implied.

The inferred abundance of Fe/O $\simeq 3 \times$ solar is rather high, given the high redshift of the object (Hasinger et al. 2002). Taken at face value, it implies an efficient iron production mechanism in the early universe and provides independent evidence for the presence of a cosmological constant (see Fig. 4 of Komossa & Hasinger 2003).

The unusual strength of the iron features and the indications for strong variability make APM 08279+5255 an excellent target for simultaneous, deep follow-up observations with Chandra and XMM-Newton.

4.2 Absorption in high-redshift quasars

Evidence for excess X-ray absorption was found in high-redshift, mostly radio-loud, quasars (e.g., Wilkes et al. 1992, Elvis et al. 1994, Schartel et al. 1997, Yuan et al. 1998, Vignali et al. 2001). The ionization state of the absorber remained largely unknown. However, there is now growing evidence that these absorbers are ionized, not neutral. As shown by Schartel et al. (1997) the spectrum and spectral changes of the high-redshift quasar PKS 2351-154 ($z=2.67$) are well explained by the presence of an ionized absorber of column density $\log N_w = 22.4$ which changes its ionization state in response to intrinsic luminosity changes of the quasar. PKS 2351-154 is one of the very few high-$z$ quasars which show a
variable UV absorption system as well. For several years, this quasar held the record of being the most distant X-ray warm-absorber candidate known, recently exceeded by GB 1428+42 and PMN J0525-33 (Fabian et al. 2001a,b).

Among the open questions related to absorption in (distant) quasars are: What is the origin and nature of the high-z excess absorbers? Is this material preferentially warm or cold? Why has it been more abundant in the past? How does it evolve? Why is excess absorption mainly seen in high-redshift radio-loud quasars whereas a number of (non-BAL) high-z radio-quiet quasars appear to be absorption-free? Answers to these questions are crucial for understanding the formation and evolution of AGN. Apart from measuring ionic column densities, a very interesting prospect is to determine element abundances in dust and gas at high redshift.

4.3 Quasars beyond redshift 5

Chandra and XMM were used to search for and successfully detect X-rays from the highest redshift quasars, identified in the course of the SDSS (e.g., Brandt et al. 2001, z=5.80; Mathur et al. 2002, Brandt et al. 2002, Bechtold et al. 2002, Schwartz 2002, z=5.82, 5.99 and 6.28) and discovered through the Chandra multiwavelength project ChaMP (Silverman et al. 2002; z=4.93), presently the most distant X-ray selected quasar. Most of the highest redshift quasars tend to be underluminous in X-rays. It is presently being investigated whether this is due to evolutionary effects in the spectrum or the amount of absorption, or something else. The detailed analysis of accreting black holes in the early universe, i.e., the highest redshift quasars, will also be a major goal of future X-ray missions.

The status of the identification of many nearby and distant AGN in deep fields, and the implications, is summarized by G. Hasinger (these proceedings) and Hasinger (2003).

5 Future X-ray missions

While current X-ray missions like Chandra and XMM-Newton are still expected to provide many new exciting results, the new generation of X-ray survey missions will constitute a very useful supplement, by repeatedly re-scanning the whole X-ray sky. This will lead to detections of numerous new X-ray sources, and all kinds of unusual variability events among AGN. Among the planned missions are LOBSTER (Fraser 2001), ROSITA (Predehl 2003), and MAXI (Mihara 2001) which will cover different energy bands with different spatial and spectral resolution. In the long run, follow-ups of Chandra and XMM will come: the Japanese missions ASTRO-EII and NeXT (Kunieda 2001), the US mission Constellation-X (White & Tananbaum 2001) and the European mission XEUS (Parmar 2003), the latter two presently planned to be launched in the 2012-2015 time frame. These will combine wide energy coverage with high sensitivity and spectral resolution and with medium spatial resolution.

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