The X-ray evolving universe: (ionized) absorption and dust, from nearby Seyfert galaxies to high-redshift quasars

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Abstract. Cold and warm absorbers have been detected in all types of active galaxies (AGN) from low to high redshift. This gas, located in the black hole region of AGN, is thought to play an important role in AGN unification scenarios, in explaining the X-ray background, in black hole growth and AGN evolution.

High-resolution spectroscopy with Chandra and XMM-Newton has recently revealed the signatures of warm absorbers in the form of many narrow absorption lines from highly ionized material. The richness in spectral features will provide a wealth of information on the physical processes in the central region of the few X-ray brightest, most nearby Seyfert galaxies. The long-term goal is to obtain this information for a much larger number of objects, particularly at higher redshift. This will be possible with the future X-ray observatory XEUS.

We provide a review of the observations of dusty and dust-free warm and cold absorbers at low and high redshift, including most recent results and exciting questions still open. Emphasis is on the science issues that we will be able to address with XEUS for the first time, particularly at high redshift, including: (i) determination of metal abundances of X-ray (cold) absorbers by detection of metal absorption edges, (ii) analysis of the composition of dust mixed with cold and ionized gas (K-edges of metals in cold dust and cold gas will be resolvable from each other for the first time), (iii) measurement of the velocity field of the gas, (iv) utilization of these results to investigate the evolution of gas and dust in AGN from high to low redshift: the evolution of abundances, dust content, ionization state, amount and velocity of gas, and its role in feeding the black hole.

We emphasize the importance of iron absorption measurements with XEUS at high redshift for two key issues of cosmology: the early star formation history of the universe, and the measurement of cosmological parameters. As an example, we discuss recent XMM-Newton observations of the high-redshift BAL quasar APM 08279+5255.

1. Introduction

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 and, in particular, allow to measure elemental abundances at high redshift, with profound consequences for our understanding of the star formation history in the early universe.

Here, we provide a short overview of previous X-ray observations of absorption in AGN, and discuss how exciting questions still open can be addressed with the XEUS observatory. We apologize in advance for incompleteness in citations due to space limitations.

2. (Warm) absorbers in nearby Seyfert galaxies

2.1. Dust-free and dusty ionized absorbers

With ROSAT, the signatures of warm absorbers, absorption edges of highly ionized oxygen ions at \( E_{\text{OVII}} = 0.74 \) keV and \( E_{\text{OVIII}} = 0.87 \) keV, were first detected in the X-ray spectrum of MCG–6-30-15 (Nandra & Pounds 1992), following earlier Einstein evidence for highly ionized absorbing material in AGN (Halpern 1984). Detailed studies of many other AGN followed, and the signatures of warm absorbers have now been seen in about 50% of the well-studied Seyfert galaxies (e.g., George et al. 1998; see Komossa 1999 for a review). First constraints placed the bulk of the
ionized material outside the BLR (e.g., Mathur et al. 1994, Komossa & Fink 1997b). Depending on its covering factor and location, the warm absorber may be one of the most massive components of the active nucleus.

Some (but not all) ionized absorbers were suggested to contain dust, based on otherwise contradictory optical–X-ray observations (e.g., Brandt et al. 1996, Komossa & Fink 1997b, Komossa & Bade 1998). The first possible direct detection of Fe-L dust features in the X-ray spectrum of MCG–6-30-15 was recently reported by Lee et al. (2001). See Komossa (1999) for a pre-Chandra/XMM review on warm absorbers.

*Chandra* and XMM-Newton detected a wealth of absorption features originating from ionized gas in nearby Seyfert galaxies (e.g., Kaastra et al. 2000, 2002; Kaspi et al. 2000, 2001; Sako et al. 2001; Collinge et al. 2001; Branduardi-Raymont et al. 2001; Lee et al. 2001; Komossa et al. 2001; Netzer et al. 2002; Yaqoob et al. 2002). These observations confirmed the presence of ionized absorbers, but also showed that spectra are more complex than previously modeled: The ionized absorbers are often multi-component, with a range of ionization parameters and outflow velocities (e.g., Kaastra et al. 2002, Kaspi et al. 2001), and absorption-dips previously mainly attributed to oxygen edges are in some cases similarly well or better explained by Fe-M absorption-line complexes (e.g., Sako et al. 2001, Behar et al. 2002).

In the case of MGC–6-30-15 a discussion has started on how much of the “saw-tooth” spectral structure at soft X-ray energies originates from a warm absorber (which is independently detected by narrow absorption lines; Branduardi-Raymont et al. 2001, Lee et al. 2001), or whether it is dominated by relativistically broadened accretion-disk lines (Branduardi-Raymont et al. 2001, Fabian 2001).

The presence of ionized absorbers may also be responsible for a number of X-ray phenomena in X-ray-weaker objects, where previous X-ray spectroscopy did no longer allow to resolve individual spectral features from the absorber, but the collective effect of the absorbing gas on the X-ray spectrum is still visible. We give two examples: for instance, (i) with *ROSAT* it was generally not possible to distinguish between black bodies and ionized absorbers to account for the very steep observed soft X-ray spectra of Narrow-line Seyfert-1 galaxies (Komossa & Fink 1997a). (ii) The idea that variations of the ionized absorber in response to intrinsic luminosity variations can mimic continuum-shape variations in case of insufficient spectral resolution is an old one, and was discussed in the early days of warm-absorber studies (e.g., Kunieda et al. 1992). More recently, it was applied to some cases of unusual variability among AGN: the narrow-line Seyfert 1 galaxy RXJ0134-4258 (Komossa & Meerschweinchen 2000) and the Seyfert galaxy NGC 3516 (Netzer et al. 2002).

### 2.2. Cold absorption

Cold absorption plays a fundamental role in Seyfert galaxies of type 2. In this field, the *BeppoSAX* mission recently led to great progress: large X-ray absorption columns were measured in many Seyfert 2 and intermediate-type Seyfert galaxies, including a number of Compton-thick candidate sources (e.g., Maiolino et al. 1998, Guainazzi et al. 1999, Bassani et al. 1999). According to Bassani et al., the mean absorption column in Seyfert 2 galaxies is about $N_H \approx 10^{23.5}$ cm$^{-2}$, while about 20-30% of the sources of their sample exceed $N_H > 10^{24}$ cm$^{-2}$. The X-ray absorption columns appear to be variable on the timescale of months to years (e.g., Risaliti et al. 2002). Interestingly, some Seyfert galaxies seem to change their X-ray spectra from reflection-dominated to transmission-dominated within several years (Guainazzi et al. 2002, and ref. therein). For the relevance of cold absorption in the context of models for the X-ray background, see Hasinger (these proceedings).

![Fig. 1. High-resolution X-ray spectrum of NGC 5548 (Kaastra et al. 2000) obtained with the LETGS aboard Chandra. The inset shows a zoom of the OVII triplet to which a resonance line, two intercombination lines (unresolved), and a dipole-forbidden line contribute.](image-url)
2.3. Open questions which we will be able to address with XEUS

Chandra and XMM-Newton provided high-quality spectra for the nearest Seyfert galaxies. The long-term goal is to obtain this information for a much larger number of objects, particularly at higher redshift. High spectral resolution and sensitivity will allow to detect even weak lines, measure line-profiles, resolve multiple components, perform line-reverberation mapping in X-rays, and obtain the velocity fields of the absorber(s).

Questions of particular interest are: how many components are warm absorbers composed of ?, what are their densities, locations, covering factors, and metal abundances ?, is the ionized material in or out of photoionization equilibrium ?, is the velocity field similar to that measured in the UV ? Finally, are UV- and X-ray absorber identical (e.g., Mathur et al. 1997, Brandt et al. 2002)?, what is the origin and evolution of ionized absorbers ?

Concerning dusty warm absorbers, dust-created metal K-shell absorption edges will be spectrally resolvable from gas-created K-shell edges for the first time. Measuring dust absorption in X-rays will be a powerful new tool to determine the dust composition in other galaxies (e.g., Komossa & Bade 1998, Komossa 1999).

Finally, all kinds of peculiar or extreme properties of AGN, partly suggested to be linked to ionized absorption (e.g., Komossa & Meerscheinchen 2000), can be studied with XEUS observations of high resolution and sensitivity.

3. Broad absorption line (BAL) quasars

3.1. Previous observations

BAL quasars are characterized by broad UV absorption lines. Is 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). Although 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) almost all data still suffer from low S/N (typically 50 to few hundred X-ray photons detected). There 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 we are aware of. A recent XMM-Newton observation led to the detection of a strong absorption feature of ionized iron, interpreted as K-edge, arising from a warm absorber of high

![Fig. 2. 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.](image-url)
column density (Hasinger et al. 2002; for Chandra results on this quasar, just posted at astro-ph, see Chartas et al. 2002).

No doubt, APM 08279+5255 is a top target for XEUS (see also Section 6).

3.2. Open questions which will be addressed with XEUS

One basic question related to the X-ray BAL flow is: are we directly seeing the outflowing gas in X-rays, or is the X-ray absorber at rest, shielding the UV absorbing gas to ensure the line-driving remains effective even for high ionization parameters? Are UV and X-ray absorber identical? Is radiation pressure from UV lines indeed the main driving mechanism of the outflow? What are the X-ray column densities and the corresponding mass outflow rates? What is the geometry of the BAL flow?

Of fundamental importance will be the simultaneous measurement of column density and outflow velocity of the gas. (With present X-ray missions, and as long as the X-ray spectrum is dominated by iron absorption edges it is very difficult to distinguish between dominant ionization stage and outflow velocity of the gas.) Such measurements will allow to solve one major uncertainty in BAL models, mentioned above: is the (high-column-density) X-ray absorber outflowing with high speed, or at rest? In fact, the high X-ray column density measured in some BALs, most reliably for APM 08279+5255, in combination with high outflow velocities would pose a problem for radiation-driven outflows (see, e.g., discussion by Hamann 1998) and may give indications that other mechanisms are at work to drive the BAL flows. The new X-ray measurements with XEUS will have profound implications for our understanding of massive and energetic outflows in AGN, their launch and acceleration mechanism.

Abundance measurements will tell the history and origin of the BAL gas, and its role in metal-enriching the environment. According to a recent model by Elvis et al. (2002), BAL environments are expected to be dusty. In the X-rays regime, absorption features from dust will provide a clean way to measure the dust composition.

4. Absorption in high-redshift quasars

4.1. Previous observations

Evidence for excess X-ray absorption was found in high-redshift, mostly radio-loud, quasars (e.g., Elvis et al. 1994, Schartel et al. 1997, Yuan 1998). The ionization state of the absorber remained largely unknown. However, there is now growing evidence that these absorbers are not cold but warm. 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 \( N_{\text{w}} = 22.4 \) 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). In contrast, Yuan et al. (2000) argued that the X-ray absorber of the high-redshift quasar RXJ1028.6-0844 is very likely cold. An interesting puzzle is, why the UV spectrum of this object does not show any signs of the X-ray cold absorber.

![Fig. 3. Best-fit warm absorber which was used to model the X-ray spectrum of the \( z = 2.69 \) quasar PKS 2351-154 in high-state (upper curve) and low-state (lower curve; Schartel et al. 1997). For even higher redshifts, edges of the ionized absorber are shifted ever closer to the low-energy sensitivity cut-off of current X-ray instruments. In case of insufficient S/N, the edges and lines of the warm absorber may easily be confused with cold hydrogen absorption, and thus mimic the presence of a cold absorber of high column density (Komossa, e.g., 1999).](image)

1 Chartas et al. presented a Chandra spectrum of APM 08279+5255 and modeled the absorption structure by two iron absorption lines which then have huge outflow velocities of 0.2 and 0.4c. Both observations are consistent with each other, if variability is assumed.
4.2. Open questions which will be addressed with XEUS

What is the origin and nature of the high-z excess absorbers? Is this material 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. This topic will be discussed in more detail in Section 6.

5. Absorption lines from the intergalactic medium

An exciting new aspect of having access to high-resolution spectroscopy in X-rays is the search for absorption lines from the intergalactic medium. First results were recently reported by Mathur et al. (2002). (Weak) OVII and OVIII absorption lines in the direction of the bright quasar H1821+643 were interpreted as arising from a moderate density, shock-heated intergalactic medium predicted by cosmological scenarios. (See Fang et al. 2002 for detection of OVIII Lyman-alpha absorption from intra-group gas along the sightline towards PKS 2155-304).

With XEUS, we will be able to measure more lines of sight, and greatly improve the statistics, to measure reliably high-ionization lines from filaments of low column density.

6. Prospects for studying absorbers at high redshift with XEUS: constraints on early star-formation history and cosmological parameters from iron abundance measurements

The spectral richness and complexity of AGN, observed with Chandra and XMM, will provide a wealth of information on the physical processes in the central region of the few X-ray brightest, most nearby Seyfert galaxies. The long-term goal is to obtain this information for a much larger number of objects, particularly at higher redshift.

We concentrate here on the aspect of deriving metal abundances at high redshift. Below, we summarize open questions and how they can be addressed with the greatly improved sensitivity and resolution (Arnaud et al. 1999) of XEUS.

6.1. Abundances at high redshift: constraints on early star-formation history of the universe, and on cosmological parameters

Two types of quasars show excess absorption at high redshift: radio-loud quasars on the one hand, BAL quasars on the other hand. (Interestingly, though, very few BALs are radio-loud; but whether these facts tell us something about the similar/different origin of the excess absorbers in both types of objects, is unclear.)

Here, we will concentrate on the iron edge features which offer some valuable advantages over Fe emission lines in usage as abundance indicators (for interesting aspects of studying relativistically broadened iron lines at high redshift we refer to the XEUS science case; Arnaud et al. 1999).

The iron absorption features and K-edges provide a unique probe of matter at high redshift because, firstly, they are easy to measure even, or, particularly, at high redshift z, and secondly, Fe(\text{O}) abundance measurements in the early universe are important for key issues of cosmology, as elaborated on below. The relevance of UV-FeII emission in deriving Fe/Mg abundances at high z was discussed by Hamann & Ferland (1999) and Yoshii et al. (1998). In particular, Yoshii et al. (1998) used the emission-line ratio FeII/MgII to estimate the iron-to-magnesium abundance in the distant quasar QSO B1422+231. Here, we would like to emphasize the role of the X-ray FeKα edges as one of the ‘cleanest’ diagnostics of iron – of column density and ionization state in a first step, and of Fe/O abundance in a second step:

– Firstly, the iron absorption is easy to measure: At high redshift, the iron-K edges are redshifted to a region, where the detector sensitivity is high. As a bonus, the continuum shape is very well constrained since redshift shifts the high-energy part of the quasar spectrum into the observable band.

– Absorption edges are, in principle, more reliable than emission lines because they do not depend on parameters like gas density and temperature, and provide a direct measurement of the ionic column densities.

In addition, the iron edge is better suited than the iron Kα emission line which appears to be less common at high redshift.
In the UV-band, no strong Fe-lines are present, apart from the FeII emission complexes which are still subject to high uncertainties, (i) in model predictions (e.g., the role of photo-excitation by Lyman $\alpha$ photons), and (ii) in measurement interpretation (some Fe may be depleted into dust, some Fe may be of higher ionization state than FeII, with reduced contribution to FeII emission in both cases); see Hamann & Ferland (1999) and references therein.

- The iron edges do not coincide with any other strong absorption-line transitions at the same energies (as opposed to some low-energy features, where K-shell and L- and M-shell features of different species partly overlap).

- Absorbers of high column density have been observed in high-redshift quasars in X-rays, particularly in radio-loud quasars and BAL quasars, so they are known to be present. A high column density is indeed required for the optical depths in the edges to become measurable. E.g., a column density in neon-like iron of $N_{\text{FeXVII}} = 10^{19}$ cm$^{-2}$ corresponds to an optical depth of $\tau = 0.27$ in the absorption edge (with cross section from Verner & Yakovlev 1995).

- The element iron plays a special role in chemical enrichment scenarios, because its production is delayed relative to other elements (e.g., Fig 1 of Hamann & Ferland 1993), since it is believed to be mostly produced in supernovae of type Ia (e.g., Nomoto et al. 1984, Sect. 2.1 of Greggio & Renzini, 1984, Sect.4.6 of Hamann & Ferland 1993, and references therein). Its role as “cosmic clock” was therefore realized early (e.g., Tinsley 1979). Hamann & Ferland (1993) also pointed out its role in determining cosmological parameters: A certain age of the universe is required to produce iron in sufficient amounts. The detection of high Fe abundances at high redshift would therefore point to a larger age of the universe at the same redshift, thus to a different set of cosmological parameters than an Einstein-deSitter universe with deceleration parameter $q_0 = 0.5$ (Fig. 4).

It is these last two science issues, which are of special interest. The usage of iron as a “cosmic clock” depends on our understanding of supernovae of type Ia, which are thought to play the dominant role in the enrichment of iron relative to alpha elements. Given the long lifetime of SN Ia precursors, it takes about 0.3-1 Gyr until SN Ia start to form in significant numbers (e.g., Fig. 9 of Hamann & Ferland 1993; Fig. 4 of Matteucci 1994). The iron production is delayed correspondingly ($t > 1$ Gyr). Therefore, even with a high rate of SN Ia, detection of large amounts of iron in the very early universe would require another mechanism to be at work. It would most likely imply a larger age of the universe at a given redshift, to provide more time for the formation of iron (Hamann & Ferland 1993, Yoshii et al. 1998).

**Fig. 4.** Age of the universe in units of $10^9$ years versus redshift for different cosmologies, using a Hubble constant $H_0 = 65$ km/s/Mpc. Upper solid line: $\Omega_m=0$, lower solid line: $\Omega_m=1$ ($\Omega_\Lambda=0$ in both cases), dashed line: $\Omega_m=0.3$ and $\Omega_\Lambda=0.7$. The dotted horizontal lines correspond to the timescale to produce a Fe/O abundance ratio of solar, 2 and 3× solar (Hamann & Ferland 1993; their model ‘M4a’), as marked in the figure. The vertical dotted line corresponds to a redshift $z = 3.91$ measured for APM 08279+5255. The filled circle with the error bar gives the timescale necessary to produce the observed amount of iron in APM 08279+5255 (based on model M4a of Hamann & Ferland). XEUS will be crucial in determining Fe abundances at high redshift. It will allow to significantly narrow down the error bars for APM 08279+5255, and to study more high-redshift objects in a similar way.

To demonstrate these issues further, we use the recent X-ray results of Hasinger et al. (2002) on the BAL quasar APM 08279+5255 at redshift $z=3.91$, which shows an Fe/O ratio of about 3. Such high ratios are not produced by SNII/Ib and imply that SN Ia are involved. However, assuming an Einstein-deSitter world model with $\Omega_m=1.0$ and $\Omega_\Lambda=0$, at the redshift of the quasar the universe was too young ($t \approx 0.9$ Gyr; Tab. 1) to produce the observed...
of the universe (in Giga years) at different redshifts for several cosmologies.

| cosmological model | age of universe | age of universe at z= |
|--------------------|----------------|---------------------|
| $\Omega_m=0$, $\Omega_\Lambda=0$ | 15 Gyr | 1.5 Gyr | 2.1 Gyr | 3.0 Gyr | 7.5 Gyr |
| $\Omega_m=0.3$, $\Omega_\Lambda=0.7$ | 14.5 | 0.6 | 1.0 | 1.7 | 6.1 |
| $\Omega_m=1$, $\Omega_\Lambda=0$ | 10 | 0.3 | 0.5 | 0.9 | 3.5 |

Table 1. Age of the universe (in Giga years) at different redshifts for several cosmologies.

overabundance of iron. According to models of Hamann & Ferland (1993; their model M4a) a timescale of $\sim 3$ Gyr is required to produce an abundance ratio of Fe/O=3.

The XMM-Newton X-ray observations of APM 08279+5255 therefore favor cosmological models which predict a slightly larger age of the universe at the redshift of the quasar, like recent models involving a low value of $\Omega_{\text{matter}}$ and a cosmological constant (e.g., Fig. 7 of Perlmutter et al. 1999). The idea is illustrated in Fig. 4, which plots the age of the universe in dependence of redshift $z$ (e.g., Carrol et al. 1992) for several cosmological models.

The excellent spectral resolution and sensitivity of XEUS will not only allow us to scrutinize the presence of the iron feature in APM 08279+5255 and its interpretation, it will also provide similar information for many more objects. We will thus obtain valuable information about nucleosynthesis in the early universe, and we will be able to follow another path to measure cosmological parameters.

6.2. Soft X-ray sensitivity of future X-ray missions

An important design feature of future X-ray missions, particularly those aiming at high-redshift studies, is the soft X-ray sensitivity. In order to determine metal abundance ratios of Fe/O and Fe/Ne, it will be essential to detect oxygen and neon edges out to as high redshift as possible. The high sensitivity of XEUS in its final configuration will be crucial to study iron absorption features at high redshifts, since the iron abundance is expected to decline significantly beyond a redshift $z \approx 4$, as discussed above.

7. Summary

Science issues that we will be able to address with XEUS for the first time, particularly at high redshift, include: measurement of metal abundances of X-ray (cold) absorbers by detection of metal absorption edges, determination of the composition of dust mixed with cold and ionized gas (K-edges of metals in cold dust and cold gas will be resolvable from each other for the first time), measurement of the velocity state of the gas, and usage of these results to investigate the evolution of gas and dust in AGN from high to low redshift: the evolution of abundances, dust content, ionization state, amount and velocity of gas, and its role in feeding the black hole.

A particularly exciting aspect is to use the iron absorption features, especially the K-edges, for abundance determinations, which will have fundamental implications for our understanding of the early star formation history of the universe, and which will provide another means to measure cosmological parameters. In order to determine Fe/O and Fe/Ne ratios out to large redshifts, soft X-ray energy sensitivity (to reliably measure O, Ne) of future X-ray missions is essential.

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The timescale to reach an abundance ratio of Fe/O=solar is at least 1 Gyr in all models of Hamann & Ferland (HF93), and is basically given by the lifetime of SNIa precursors. Different models of HF93 then predict a different evolution of F/O, and we caution that in model predictions there is some scatter in the time at which Fe/O reaches 3x solar. Model ‘M4’ is the quasar model favored by HF93. In several other models they studied, Fe/O never reaches 3x solar, whereas in their extreme model ‘M6’ (cf. their Fig. 1) Fe/O reaches 3x solar already after 2 Gyr.

For that purpose, the edges have to be disentangled from other potential absorption lines at similar energies, and any potential black body contribution at the softest X-ray energies has to be measured carefully, since it can influence the oxygen-ionization structure, thus affecting the measured ratio of Fe/O and Fe/Ne (Hasinger, Komossa et al., in prep.). The possibility of partial re-filling of absorption features due to scattering also has to be kept in mind carefully.
