

High spectral resolution X-ray observations of AGN

J.S. Kaastra^{1,2,*}

¹ SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, Netherlands

² Astronomical Institute, Utrecht University, P.O. Box 80000, 3508 TA Utrecht, Netherlands

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A brief overview of some highlights of high spectral resolution X-ray observations of AGN is given, mainly obtained with the RGS of XMM-Newton. Future prospects for such observations with XMM-Newton are given.

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1 The importance of AGN outflows

Active Galactic Nuclei (AGN) are powered by accretion. Nevertheless, apart from inflow of gas, observations have shown also the presence of high velocity outflows. The most extreme ones are the Broad Absorption Line Quasars, with outflow velocities reaching a significant fraction of c . Less extreme outflows are more common. Statistical studies indicate that roughly half of all low luminosity Seyferts have outflows (X-rays: George et al. 1998; long wavelength UV: Crenshaw et al. 1999; O VI: Kriss 2006). The outflow velocities in these cases are in the 100–1000 km s^{−1} range, but also smaller and larger velocities occur, see for instance Kriss (2006). The presence of warm ionising gas in the line of sight towards AGN was already found through the presence of broad X-ray absorption troughs deduced from Rosat PSPC spectra and later confirmed with better spectral resolution from ASCA data. However, these instruments had insufficient spectral resolution to measure any outflow velocity of this warm absorber, as they essentially detected the broad and blended continuum absorption edges of ions such as O VII and O VIII. With the advent of high resolution X-ray grating spectrometers (the Chandra LETGS and HETGS; XMM-Newton RGS) the situation changed dramatically. The first AGN observed with high spectral resolution was NGC 5548 (Kaastra et al. 2000); its spectrum showed dozens of strong, blue-shifted absorption lines from a photoionised, outflowing wind. Low amounts of absorbing gas can only be traced by their absorption lines as the absorption edges are less deep. Therefore the availability of high-resolution observations allowed a major leap forward in the study of AGN outflows. Contrary to the UV band where only a few ions can be traced, the X-ray band contains diagnostic ions from many different chemical elements and with a broad range of ionisation potential.

AGN outflows are not only interesting because of these phenomena themselves, but the study of the outflows bears

importance for a broad range of astrophysical topics. Several hundreds of papers have been written about that, and we refrain from giving here a complete literature overview. Instead, we only mention the relevant topics. The growth of the supermassive black hole can be affected by strong outflows, and therefore also the AGN luminosity function is affected by outflows. These outflows enrich the intergalactic medium, and through feedback processes therefore contribute to the evolution of the host galaxy. On larger scales, they can be intimately linked to cluster cooling flows, and also the magnetisation of the galactic and intracluster gas is affected by the details of the outflow. However, the absolute strength of the outflows and therefore its precise contribution to all these processes is not well known. It all depends on the mass flux, kinetic luminosity and chemical abundances of the outflow. A key issue here is the distance of the outflow from the central black hole. We come back to that in Sect. 3.

2 The zoo of AGN

After the launch of Chandra and XMM-Newton, many AGN have been observed with these instruments. XMM-Newton has the advantage that all observations give simultaneously a CCD spectrum (EPIC) and a grating spectrum (RGS). Below a few highlights of RGS observations of AGN are given.

The RGS spectrum of the brightest Seyfert 2 galaxy, NGC 1068, proved unambiguously the dominance of photoionised gas in these sources (Kinkhabwala et al. 2002). A deep 280 ks spectrum of the Seyfert 1 galaxy NGC 3783 showed the diagnostic power of the oxygen line region between 17–24 Å with lines from all ions of O IV–O VIII detected (Behar et al. 2003). The discovery of an unresolved transition array (UTA) of iron lines in IRAS 13349+2438 opened a new window to study the most lowly ionised absorption components in AGN outflows. The RGS spectrum of NGC 5548 opened the discussion of whether the absorber is in the form of clouds in pressure equilibrium or in a more

* Corresponding author: j.kaastra@sron.nl

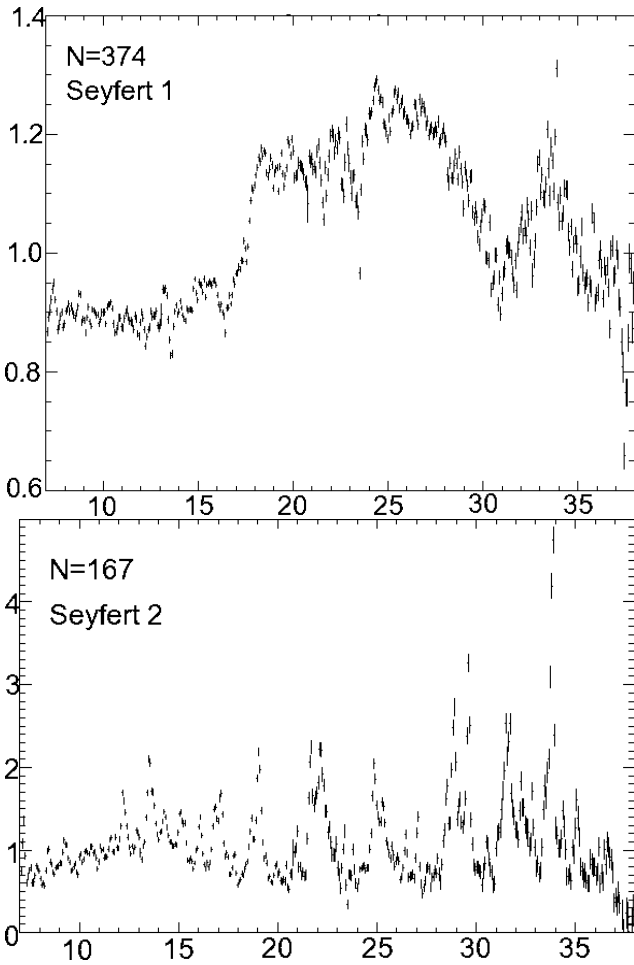


Fig. 1 Average RGS spectra for Seyfert 1 galaxies (upper panel) and Seyfert 2 galaxies (lower panel). The number of spectra is indicated by N . Spectra are displayed as $\text{phot cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ versus wavelength (\AA).

continuous form (Steenbrugge et al. 2003). Finally, the reported strong relativistic oxygen and nitrogen emission lines in MCG–6–30–15 (Branduardi-Raymont et al. 2001; Sako et al. 2003) showed the complexity of AGN spectra and led to intense discussions on the importance of relativistic lines versus dusty warm absorbers.

The AGN phenomena has many different manifestations in the X-ray band, and almost no two spectra are the same. The differences do not only exist in the difference between broad classes, such as Seyfert 1 versus Seyfert 2, or Seyferts versus quasars, or blazars with their nonthermal jet pointing towards the observer versus other QSO. Also within each class there are large differences, for instance in the presence of an outflow, the number of outflow components, the outflow velocities and column densities, the distribution of ionisation parameter, and in the presence and strength of emission lines on all broadening scales from narrow (few 100 km s^{-1}) to broad (few 1000 km s^{-1}) to relativistic lines.

In order to illustrate some of the differences, Figs. 1 and 2 show the stacked RGS spectra of all observed sources

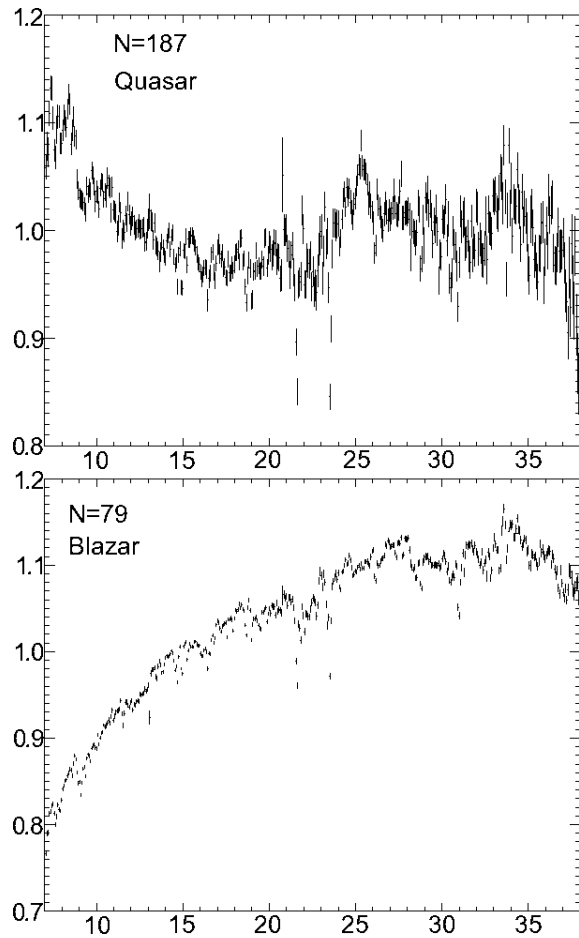


Fig. 2 Average RGS spectra for quasars (upper panel) and blazars (lower panel). The number of spectra is indicated by N . Spectra are displayed as $\text{phot cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ versus wavelength (\AA).

within four different AGN classes. These spectra have been obtained simply with a few mouse-clicks using the Browsing Interface for RGS Data (BiRD) tool¹. The spectra are rebinned by a factor of two, and are corrected for the redshift of the source and Galactic absorption. Some caveats should be made here: it may be possible that some sources are mis-classified, and also here no quality filter was applied. Furthermore, the spectra may be dominated sometimes by a small number of long exposures of bright individual sources. For any serious scientific analysis, the spectra should be extracted with dedicated care from the archive and then analysed. Nevertheless, already these raw, stacked spectra show interesting features. In the Seyfert 1 spectrum, the broad emission-like features between $17\text{--}30 \text{ \AA}$ are at least qualitatively similar to the broad relativistic oxygen and nitrogen lines found in MCG–6–30–15 by Branduardi-Raymont et al. (2001) (or compatible with several alternative models proposed recently). The Seyfert 2 spectrum shows the same strong emission lines and narrow radiative

¹ <http://xmm.esac.esa.int/BiRD/>

recombination continua as first discovered in NGC 1068 (Kinkhabwala et al. 2002); see also Guainazzi & Bianchi (2007). The stacked quasar spectrum shows a significant neutral oxygen absorption edge at $\lambda < 23 \text{ \AA}$ with a depth of $\sim 10 \%$, corresponding to an intrinsic absorbing column density of about 10^{24} m^{-2} , showing that this population has – on average – a moderate amount of intrinsic absorption. The blazar spectrum finally shows a relatively smooth and very soft intrinsic continuum; some remaining features are the 1s-2p line of O I from our own Galaxy which was not taken into account in the Galactic absorption correction.

3 The importance of reverberation studies

As indicated in Sect. 1, AGN outflows have importance for a broad range of astrophysical problems, but exactly how large their contribution is depends on the absolute mass outflow rate and kinetic luminosity \dot{E}_k (apart from the chemical composition).

The \dot{E}_k of a shell-like, non-accelerating outflow is given by $\dot{E}_k \simeq \frac{1}{2} \Omega R N_H m_p v^3$, where Ω is the solid angle occupied by the outflow, R the distance from the central source, N_H the total hydrogen column density, m_p the proton mass and v the outflow velocity. Spectral observations straightforwardly determine v , and Ω is expected to be $\sim \pi$ since 50 % of all Seyfert 1s show outflow signatures. N_H can be determined by integrating the column densities over the various ionisation stages. For each ionisation stage, the column density of the absorbing gas can be determined directly from the depth of the absorption features. As the X-ray band contains no hydrogen lines, UV measurements of Lyman lines is helpful to tie down the absolute abundances. The most uncertain quantity is R . In principle, R is connected to the ionisation parameter ξ by

$$\xi = L/nR^2, \quad (1)$$

with L the ionising luminosity of the central X-ray source, and n the gas density of the absorber. As L can be measured directly and ξ can be deduced from the ions that are present in the X-ray spectrum, the product nR^2 is known, but one needs to have additional information on either n or R to determine the other parameter.

There have been a few attempts to measure the density n directly from density sensitive UV lines (Gabel et al. 2004). However, the observations are difficult and it is not clear whether the derived numbers are also applicable to the higher ionised X-ray components, which carry the bulk of the kinetic luminosity. In X-rays, there are potentially density sensitive O V lines (Kaastra et al. 2004), but up to now this method has not yet revealed a robust measurement of a density.

There is a good alternative method, however, to measure densities. This is through reverberation mapping of the warm absorber. The basic idea is as follows. All AGN are time variable X-ray sources. When the X-ray flux from the central region rises or falls, also a more distant absorbing

cloud receives more or less ionising flux. This results into a net further ionisation or recombination of the absorbing medium, respectively. However the medium cannot adjust instantaneously, and the net ionisation or recombination rate depends on the gas density. The effective recombination or ionisation time scale is proportional to n . Thus, if for instance a sudden drop in continuum flux is followed by a delayed (time scale Δt) recombination, the delay time Δt determines the density and hence using Eq. (1) the distance R is known and thereby the kinetic luminosity.

A key issue in all this is of course that the source is cooperative and varies with sufficient amplitude and on a suitable time scale. Preferentially, the sampling time should be a few times larger than the typical variation time of the central source, as to allow to follow unambiguously the response of the warm absorber to a few cycles of activity. It is well known (Barr & Mushotzky 1986) that the typical variability time scale in AGN scales linearly with the central luminosity. For the most rapidly variable and X-ray bright Seyferts like NGC 4051 or MCG–6-30-15 the variability time scale of a few minutes to hours makes it impossible – with current instrumentation – to obtain reliable X-ray spectra for each “variation period”. Thus, reverberation cannot be used for these sources and at best some statistical conclusions can be derived by for example stacking spectra with similar luminosity ranges. The best cases however are the Seyferts with variability periods of the order of a day, as for the brightest Seyferts RGS needs about 50–100 ks integration time to obtain a high quality spectrum.

A second necessary condition is that the source flux variations have sufficient amplitude. For most bright Seyferts, historical data are available that allow to assess this level of variability. Nevertheless, in some cases the expected changes in the ionic column densities may be still too small to detect significantly using RGS. This can happen for instance if the absorber has a continuous distribution of column densities $N_H(\xi)$, and if in the absorber gas parcels with a decreasing ionisation parameter ξ are partially substituted with gas that originally had a higher ionisation parameter. In those cases, the combination of RGS with EPIC provides the answer. While RGS measures accurately the average ionisation distribution $N_H(\xi)$ through the measurement of individual ionic column densities, the high throughput of EPIC allows to determine the time variations of these column densities by comparing the integrated spectra over specific diagnostic wavelength intervals.

We note that the broad range of ions and ionisation parameters accessible in the X-ray band is unique and helps to measure R . As shown in Fig. 3, all ions have distinct, characteristic variability time scales.

Up to now, such important reverberation measurements have not yet been performed. There is a handfull of sources where such measurements can be made using a monitoring campaign that takes up a total integration time of the order of a Ms per source. It would be important if XMM-Newton would perform a few of such campaigns in the com-

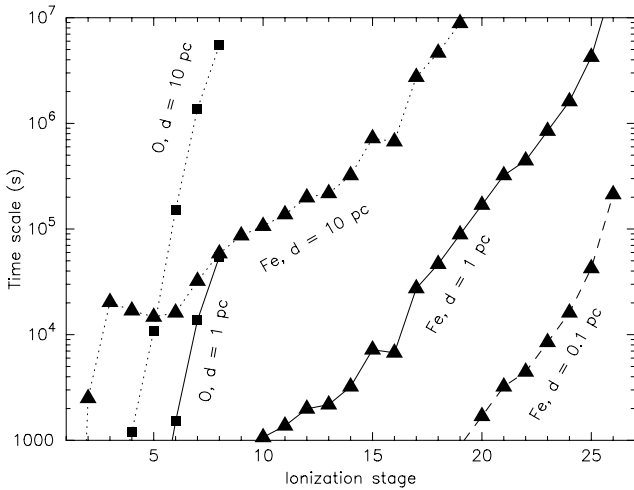


Fig. 3 Response time scales to continuum variations for different ions in a typical bright AGN. Curves are drawn for different values of the gas density n in the absorber. A measurement of a response time for a given ion therefore immediately yields the density.

ing years, as this is the only way to measure the key parameter of the kinetic luminosity of AGN outflows.

4 The need for larger samples of high quality spectra

As discussed in Sect. 2, there is a wide variety in the X-ray spectra of AGN. Just to mention a few: the presence of a warm absorber, relativistic lines, normal broad lines, dust, luminosity differences, orientation angles, etc. Possible correlations between these properties make it necessary to have sizeable samples of sources with good spectra in order to understand all these properties in their proper context and to be able to answer the fundamental astrophysical questions. Unfortunately, the number of sources with RGS spectra of sufficient quality is limited as we show below.

The most important diagnostic region is the oxygen region. At a fiducial wavelength of 23 \AA (near the O I edge) the effective area of RGS (1 CCD only) is 40 cm^2 . For a typical resolution element (FWHM) of 0.07 \AA at that wavelength, and demanding a minimum signal to noise ratio per resolution element of 10, the required integration time t_{exp} in ks can be written as

$$t_{\text{exp}} = 114 F^{-1} e^{N_{\text{H}}}, \quad (2)$$

with N_{H} the Galactic foreground absorption column density in 10^{24} m^{-2} and with F the 2–10 keV flux of the source in units of $10^{-14} \text{ W m}^{-2}$ ($10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$), where a power law continuum with photon index 2 has been assumed. As the 50 (100) X-ray brightest Seyfert 1 galaxies all have $F > 1.5$ (0.8), for the majority of them good RGS spectra can be obtained in 100–200 ks. Unfortunately, such data are not yet available. A quick inspection of the archive shows that of the 15 brightest Seyfert 1s only half of them reach a S/N of > 10 at the oxygen band. The best cases are

3C 273 (S/N = 50), MCG–6–30–15 (S/N = 40), Mrk 509 and NGC 5548 (both S/N = 22) and Ark 564 (S/N = 20). Further down the list, the situation is worse: of the 15 sources ranking at position 52–66 of the list, only two have measured spectra with S/N > 10 , namely Mrk 766 (S/N = 30) and NGC 4051 (S/N = 15); 6 others have S/N < 4 , while the remaining 7 sources have not been observed with XMM-Newton.

In most cases, for the archived spectra the main driver for the exposure time was a study of the Fe-K complex using EPIC. These exposures are often too short to give a good quality RGS spectrum (S/N > 10). However it is rewarding to invest these exposure times; for the canonical RGS spectrum with S/N = 10 at oxygen, the full pn spectrum yields about 10^6 counts, or roughly 10^5 counts in the 2–10 keV band; at this level, relativistic iron lines with an equivalent width as small as 30 eV can be detected (Guainazzi et al. 2006, Fig. 2); alternatively, in the presence of stronger iron lines, variability can be studied using such exposure times.

5 Conclusions

A reverberation program with 3 or 4 well sampled sources, each with about 1 Ms exposure time, holds the clue to determining the kinetic luminosity of AGN. To better understand the broad variety of AGN, better RGS spectra (100–200 ks exposure per target) of a larger, well-chosen sample are needed.

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