High-resolution X-Ray spectral diagnostics of Active Galactic Nuclei

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Chapter 9

Summary and outlook

Three out of the six articles presented in this thesis are based upon our study of the well known Seyfert 1 galaxy NGC 5548. The main conclusions derived in this thesis are therefore based upon the study of high signal-to-noise ratio spectra of NGC 5548. These conclusions are detailed separately from the conclusions drawn from our analysis of NGC 4593, IC 4329A and Ton 1388. In this Chapter we also discuss future studies which can be done with current instrumentation or require new missions, such as Astro-E2. Finally we give a short discussion on the need for improvements in atomic data to be able to fully exploit the current and future spectra.

9.1 Results from NGC 5548

9.1.1 Relation between UV and X-ray absorber

An important question before the advent of high resolution X-ray spectroscopy was whether the absorption detected in the UV band and the X-ray band were from the same medium, or were unrelated. From low resolution spectroscopy it was known that there is a one to one correlation between UV and X-ray absorbers. However, it did seem that the ionization parameter and the column densities detected in the X-ray were sufficiently different to suggest that these were different absorbers (Crenshaw et al. 2003, however see Mathur, Elvis & Wilkes 1995 for a different view). In Chapter 4 we report the detection of an O VI absorption line in the XMM-*Newton* spectrum of NGC 5548. An O VI absorption line, from a different transition, was already detected in the UV band, clearly establishing a relation between absorption observed in both wavelength bands. However, the column density measured in the X-ray band is still an order of magnitude larger than the column density measured in the UV band. An elegant solution to this conundrum was proposed by Arav et al. (2002; 2003). In the proposed method one can only determine lower limits to the column densities from UV observations. This restriction is due to non-black saturation, i.e. although the line is saturated, the flux measured at the particular wavelength is not zero. This non-black saturation results from a geometry where the absorber does not cover the narrow emission line region. A second reason for this restriction is the velocity dependent covering factor, i.e. the line profile is due to the covering factor, and not intrinsic to the line.

In Chapter 5 we took advantage of the higher spectral resolution of the *Chandra* spectrometers to determine the velocity structure of the absorption lines detected in the X-ray spectra of NGC 5548. The measured velocity structure is consistent with the velocity structure determined from simultaneous UV spectra (Crenshaw et al. 2003). Especially, in the X-ray spectra we resolve the highest outflow velocity component, namely the $-$ 1041 km s^{-1} component over a wide range in ionization parameter containing ions such as lowly ionized O V and highly ionized Si XIV. This indicates that within the error bars the X-ray and UV absorbers have the same kinematics. In addition, the X-ray absorber spans a range in ionization parameter that overlaps with the ionization parameter derived from the UV absorber. These conclusions firmly establish the fact that the UV and X-ray absorber are different manifestations of the same phenomenon.

9.1.2 Geometry of the absorber

The accretion disk emits radiation in the extreme UV and soft X-ray band, i.e. the soft excess component. The radiation emitted by the disk is Compton scattered by soft electrons to produce the hard X-ray continuum observed. Thus by studying AGN in the X-ray band, we study the geometry of the direct surroundings of the central SMBH. The main difference between the two models presented in Chapter 1 is the inclination angle under which one expects to observe a Seyfert 1 or a Seyfert 2 galaxy, i.e. detect an absorption or emission spectrum in the X-ray band. However, determining the inclination angle of the accretion disk is rather difficult. An exciting possibility is the detection of relativistically broadened emission lines, because the line profile is a function of the inclination angle, as well as the inner radius and the emissivity distribution. However, relativistically broadened emission lines are less frequently detected than was expected based upon ASCA low resolution spectra.

A second difference is the opening angle of the outflow or ionization cone. In the standard picture there is an ionization cone, with a rather large opening angle of about 45° along which clouds are outflowing (Urry & Padovani 1995). The observed absorption is presumably formed in this cone. In the picture by Elvis (Elvis 2000) the outflow occurs in rather narrow streams. In Chapters 4 and 5 we calculate the opening angle of the outflow from the ionization distribution and outflow velocity measured for the warm absorber, adopting Schwarzschild geometry. For the assumptions of steady state accretion and a mass accretion rate lower than the Eddington accretion rate, we determine using the formulae for mass accretion rate, mass loss rate and ionization parameter an upper limit to the opening angle between 0.07 and 10^{-7} sr. Assuming a Kerr geometry, the opening angle is nearly an order of magnitude smaller. This indicates that the absorption occurs in narrow streams. The lowest ionized absorber has the smallest opening angle while the highest ionized absorber has the largest opening angle.

From the derived opening angle it seems that the lowest ionized absorber is in the center of the outflow, which has a density gradient perpendicular to the flow direction. Such a picture is very similar to the outflow geometries obtained by Proga et al. (2000) in their simulations of radiation driven winds. In a wind with a density gradient, there is a continuous ionization distribution perpendicular to the flow, instead of different clouds having different ionization states. In Chapters 4 and 5 we show that most of the gas is highly ionized. This seems to be general property of the warm absorbers observed with high spectral resolution instruments, and seems consistent with the results obtained from wind simulations by Proga et al. (2000). From the small opening angle of the outflow it seems that the model by Elvis (2000) better describes the warm absorber.

9.1.3 Ionization structure

We conclude in Chapter 4 that the ionization structure of the warm absorber is consistent with a continuous distribution in ionization parameter. In Chapter 5 we obtained a very good fit to the LETGS and HETGS spectra of NGC 5548 with a model assuming a continuous ionization distribution. In the same Chapter we indicate that, if the ionization distribution has discrete components, then at least five components are needed to explain the spectrum. Of these five ionization components at least the lowest ionized and possibly the highest ionized component cannot be in pressure equilibrium with the other ionization components. More generally, the observed UV absorber can not be in pressure equilibrium with the higher ionized X-ray absorber. However, the above conclusions can not prove that the ionization structure is continuous, as there are other confinement methods possible such as confinement through magnetic fields.

From our analysis we argue that in the case of NGC 5548 the ionization distribution is continuous and has a power law distribution. Neither the standard model (Urry &

Padovani 1995) nor the model by Elvis (2000) predicts a continuous ionization distribution, as both models rely on clouds in pressure equilibrium confined by a hot gas. Interestingly, the highest velocity outflow component seems to have a different ionization distribution. Namely, the ratio for highly ionized gas over lowly ionized gas is substantially higher than for the other velocity components.

9.1.4 Can the outflow escape?

An important question regarding the matter distribution surrounding the SMBH is the distance of the warm absorber from the central SMBH. This distance is important in determining whether the outflow can escape the SMBH and the accretion disk, or must fall back upon it. From the time lag between the measured variability in the luminosity and the ionization parameters it is in principle possible to determine the distance of the warm absorber. However, there is a caveat, in Chapter 5 we discuss that for an outflow with a density structure perpendicular to the outflow, spectral variability in the warm absorber should only be detected in the neutral or very lowly ionized absorber and possibly the highly ionized absorber, assuming a cut-off in column density for high ionization parameters. In a wind with a continuous ionization distribution it is thus not possible to estimate the distance from the ionizing source. In NGC 5548 we did not detect any spectral variability, with the exception of O V over a timespan of 2 years. Thus for this object we can not determine a distance of the warm absorber, however, we can determine the minimum distance needed for the outflow to be able to escape the SMBH and the accretion disk. In the Chapter 5 we calculate that the highest velocity outflow will escape if the distance of the outflow from the SMBH is larger than 0.58 pc. In the model by Elvis (2000) the measured outflow velocity is not the final radial velocity for the outflow, and thus the distance between the SMBH and the outflow can be even smaller.

9.1.5 Broadened emission lines

In the LETGS spectrum of NGC 5548 we detect weak broadened emission lines, similar to the broad emission lines detected in optical and UV spectra. We detect the blend of the O VII triplet emission lines with 3 σ significance, and several weaker lines. In Chapter 6 we determine the physical parameters of the medium producing the highly ionized and the simultaneously observed lower ionized UV broadened emission lines. We made a model for two different distances. We choose a distance of 2 light days, the shortest distance of the BLR derived from reverberation mapping; and a distance of 20 light days, the distance of the BLR obtained by reverberation mapping of Hβ. For both distances a single ionization parameter is sufficient to describe both the X-ray and UV lines. Although the covering factor and column density are different for the different distance models, the ionization parameter in the different distance models is the same. We thus conclude that there is a range in densities over the thickness of the broad line region. From the different covering factor and column density we conclude that we are looking through the edge of a rotationally flattened structure. These broadened X-ray emission lines should be quite common as stronger lines are detected in the *Chandra* LETGS spectrum of Mrk 279 and NGC 4151, and the XMM-*Newton* spectrum of IC 4329A.

9.2 Results on NGC 4593, IC 4329A and Ton 1388

9.2.1 NGC 4593

In Chapter 3 we analyze the LETGS and XMM-*Newton* spectra of NGC 4593. In the LETGS spectrum we detect a highly ionized absorber which causes a depression between $10 - 18$ Å. We detect also a much weaker lowly ionized absorber which is not in pressure equilibrium with the highly ionized absorber if we assume a similar spectral energy distribution (SED) to the SED of NGC 5548 and other AGN. In this spectrum an intermediate ionized absorber is very weak or missing. The missing medium ionization component is difficult to explain in both a model with clouds and a continuous density outflow. In a density stratified wind a highly ionized outflow could shield other outflows, such that we detect only highly and lowly ionized absorption. The RGS spectra are noisy, but consistent with the LETGS spectrum.

A timing analysis of the LETGS data showed that the hard X-ray power law component is more variable than the soft X-ray excess. At the end of the observation a flare occurred, for which the decay was not correlated to the change in the soft X-ray excess. The derived variability contradicts the theory that the detected hard X-ray continuum is produced by inverse Compton scattering of soft electrons from the accretion disk. The variability is consistent with the picture of magnetic flares. Several earlier observers (Dewangan et al. 2002; Turner et al. 2001) have detected similar variability properties.

9.2.2 IC 4329A

In Chapter 7 we analyze the XMM-*Newton* spectra of IC 4329A which is a Seyfert 1 galaxy seen nearly edge-on. From the reddening observed in the optical and the UV band, and the similarity of host galaxy properties with Ark 564 and NGC 3227, Crenshaw et al. (2001) conclude that this Seyfert has a dusty luke-warm absorber, i.e. an absorber including dust grains which has a rather low ionization parameter.

This dusty luke-warm absorber is located in the plane of the host galaxy at a distance greater than 100 pc from the nucleus, and is not related to the warm absorber observed in other Seyfert 1 galaxies. Indeed, in the X-ray band we detect absorption from the host galaxy. However, with the large effective area of the RGS we were able to detect a highly ionized absorber, similar to the warm absorber observed in other Seyfert 1 galaxies. The ionization structure of IC 4329A is similar to that of NGC 5548, with the caveat that for the lowly ionized absorber detected it is difficult to determine whether it is from the host galaxy or the warm absorber. We confirm earlier observations (Perola et al. 1999) that the hardness ratio for this source is independent of luminosity. This result differs from the hardness ratio results in other Seyfert 1 galaxies where in general the spectrum becomes softer with increasing luminosity.

9.2.3 TON 1388

In Chapter 8 we report the possible detection of intervening, intergalactic ionized gas, related to the Lyα absorbers detected in UV spectra. The LETGS spectrum is noisy and thus a spectrum with a higher signal-to-noise ratio is necessary to confirm the presence of these intervening absorbers. If confirmed, the absorption detected would then be a signature of highly ionized gas which is probably located in filaments between clusters of galaxies. Models show that part of the gas in these filaments must have a high temperature. This quasar does not have a strong warm absorber, and is thus an ideal source to study possible intervening absorbers. We measure an upper limits to the hydrogen column density of $10^{23.7}$ m^{-2} for an ionization parameter of $\xi = 100$ in units of 10^{-9} W m, about 1.5 orders of magnitude less than in NGC 5548.

9.3 Outlook

9.3.1 Current instrumentation

Further study is required to confirm that the ionization distribution in the case of NGC 5548 is continuous. A continuous ionization distribution model should be tested with spectra of other Seyfert 1 galaxies. Such a study should look for spectral variability and can be done with the spectral resolution of the current generation of X-ray spectrometers, but requires high signal-to-noise spectra. The spectral variability expected is different for a model with clouds than for a model with a density gradient. In the former all ionization parameters detected should vary simultaneously with a change in luminosity. In the latter only the column density, and possibly the ionization parameter of the lowly ionized and possible highly ionized absorber should vary with changes in luminosity. Another result that needs further study is whether it is a general property of warm absorbers that most of the gas is highly ionized.

From low resolution spectra it was concluded that there is a one to one ratio between UV absorbers and X-ray absorbers; however, this conclusion should be tested with high resolution spectra. The model by Elvis (2000) predicts that in 10 to 15 % of Seyfert 1 galaxies we do not see the warm absorber, due to inclination angle of the absorber.

In this thesis we determined that if the distance of the absorber from the SMBH is at least 0.6 pc then the outflow with the highest velocity can escape the SMBH. The impact of these enriched outflows on the host galaxy or the intergalactic medium should be studied. An important question is whether the gas is able to leave the host galaxy, and/or whether it is stopped by the host galaxy, possibly triggering star formation.

9.3.2 Future instrumentation

As should always be the case, the conclusions obtained in this thesis should be tested with higher spectral resolution data when they become available. In particular the continuous ionization distribution model should be tested, since with higher resolution the distinction between three ionization components, five ionization components and a continuous ionization distribution will be more significant. Better spectral resolution will allow deblending of the different outflow velocity components, which now form a blend in the X-ray band. This will give the final proof whether all the velocity components detected in absorption in the UV band have a counterpart in the X-ray band, and are thus observed over a wide range in ionization parameters. These five different outflow velocities are difficult to explain in any model with only one outflow structure, such as both models discussed in Chapter 1. This will also allow us to study the ionization distribution of each velocity component, which is now only rarely possible.

An important question related to the ionization distribution of the absorber is whether the distribution has a cut-off at the high ionization part, or whether most of the gas is completely ionized. The conclusion about the highest ionized absorber is important in estimating the mass that is outflowing in these absorbers. This result will also allow us to determine whether the highest ionized and most massive absorber is in pressure equilibrium with the lower ionized absorbers. If not, then pressure equilibrium models are ruled out, as this highest ionized component should pressure confine the other absorbers. These questions are well suited to be studied with the Astro-E2 satellite, as it will obtain high spectral resolution spectra for the high energies, using micro-calorimeters.

Higher signal-to-noise ratio data are needed to confirm and study in detail the broadened emission lines observed in some X-ray spectra. The fraction of Seyfert 1 galaxies that do show these broadened X-ray emission lines should be determined.

This should allow to determine if these broadened emission lines are consistent with the ionization measured from the optical and the UV spectra as was concluded in Chapter 6. High signal-to-noise ratio and high spectral resolution will allow us to distinguish between broadened and relativistically broadened emission lines in the soft X-ray spectrum.

An obvious open question is the dependence of the spectrum on the inclination angle of the accretion disk, which can distinguish between both models described in Chapter 1. However, the measurement of the inclination angle of the accretion disk is complicated in the absence of relativistically broadened emission lines. ASTRO-E2 will carry onboard a hard X-ray telescope that is sensitive between 10 and 700 keV, and which can be used simultaneously with the soft X-ray telescope. This will allow for the study of the reflection component in AGN, and as a result will put much tighter constraints on the relativistically broadened Fe Kα emission line. If relativistically broadened Fe Kα lines are detected they will yield a direct measurement of the inclination angle of the inner accretion disk and thus allow to distinguish between the standard model for AGN (Urry & Padovani 1995) and the model be Elvis (2000).

More sensitive instruments are needed to confirm the reported detections of the warm hot intergalactic medium. These future observations should constrain the ionization mechanism (collisionally ionized or photoionized), elemental abundances and the total amount of baryons in such a warm state. This in turn will determine if the warm hot intergalactic medium can account for the locally missing baryons.

9.3.3 Atomic data

As already mentioned in Chapter 1 there are uncertainties in the atomic data and codes used for fitting and modeling the X-ray spectra. Measuring the dielectronic recombination rates for iron are especially important, as now only estimated oscillator strengths for Fe VI to Fe XV are known. Accurate iron dielectronic recombination rates will allow iron to be fitted with the rest of the ions, without the noticed overabundance for lowly ionized iron. Fitting iron alone will allow us to derive strong constraints on the ionization distribution of the absorber due to the large ionization range sampled, and the result is independent of elemental abundances. The calculated wavelengths for lines at wavelengths above 60 Å, and inner shell lines should be improved. This will allow us to use all the ions in the analysis, and to study possible abundance effects more easily.

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