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X-ray absorption in Active Galactic Nuclei

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Abstract. We review some of the main physical and statistical properties of the X-ray absorber in AGNs. In particular, we review the distribution of the absorbing column density inferred from X-ray observations of various AGN samples. We discuss the location of the X-ray absorber and the relation with the dust absorption at optical and infrared wavelengths. Finally, we shortly review the recent findings on X-ray absorption at high luminosities and at high redshift.

1. Introduction

The X-ray absorption provides important information on the nature of the circumnuclear medium in AGNs. Understanding the physical and statistical properties of the X-ray absorption is also highly relevant to characterize the black hole accretion in the universe. Indeed, most of the AGN activity, both locally and at high redshift, is obscured. In this short paper we shortly review the main observational results in this field. Since absorption by "warm" gas is also treated by other reviews in these proceedings, "warm absorption" is only shortly discussed in Sect.2. We will then focus on the "cold absorption", by discussing it statistical and physical properties, as well as some of the recent findings at high redshift. It is important to clarify that, due to the limited space available, this review in unavoidably highly incomplete.

2. The warm absorber

At least 50% of the low resolution X-ray spectra of type 1 (optically unobscured) AGNs show the presence of a broad absorption feature at ∼0.7–0.8 keV, ascribed to absorption edges of OVIII and OVII due to a "warm", ionized gas along our line of sight (Reynolds 1997; Crenshaw & Kraemer 1999). However, the advent of grating X-ray spectroscopy with Chandra and XMM improved dramatically our understanding of warm absorbers. In particular, the recent, high resolution X-ray spectra revealed that the trough at ∼0.7–0.8 keV is actually the blend of various absorption lines and absorption edges. The 900 ks Chandra HETGS spectrum of NGC 3783 is the high resolution spectrum with the highest quality currently available, and it has been extensively used to investigate the properties of the warm absorber (Kaspi et al. 2002; Netzer et al. 2003; Krongold et al. 2003). It was found that, at least in the case of NGC 3783,

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the warm absorber has a column density of the order of a few times 10^{22} cm^{-2}, it is outflowing with velocities ranging from a few to several 100 km s^{-1} and it is located between $\sim$0.2 pc and $\sim$3 pc from the ionizing, nuclear source. According to Netzer et al. (2003) and Krongold et al. (2003) matching the several absorption lines observed in the spectrum of NGC 3783 requires the presence of two or three different phases of the absorbing medium, at different temperatures and different ionization stage, but in pressure equilibrium. However, Gonçalves et al. (2006) pointed out that multi-temperature components arise naturally in a single medium as a consequence of the stratification of the ionization structure of each cloud exposed to the nuclear source. In particular, Gonçalves et al. (2006) could fit the various absorption lines observed in NGC 3783 with a single medium, without the need for different, separate components of the absorbing medium.

3. Cold absorption: general properties and warnings

The presence of a cold, neutral medium along the line of sight introduces a sharp photoelectric absorption cutoff in the power-law spectrum emitted by the nuclear source. It is possible to accurately determine the column of absorbing material by measuring the energy of the photoelectric absorption. At $N_H > 10^{24}$ cm^{-2} the gas is thick to Compton scattering (dubbed as "Compton thick"). In this case the primary X-ray radiation is completely absorbed at energies <10 keV. However, as long as the column of gas does not exceed 10^{25} cm^{-2} the primary radiation is still transmitted and observable at energies in the range 10–100 keV. In Compton thick sources with $N_H > 10^{25}$ cm^{-2} the direct, primary X-ray radiation is totally absorbed at any energy (Matt et al. 1997).

Although, the primary radiation is totally absorbed (at least at $E < 10$ keV), Compton thick sources are still observable through radiation that is scattered into our line of sight either by a cold, Compton thick medium ("cold reflection") or, less frequently, by a warm medium ("warm reflection"), either of such scattering media must extend on scales larger than the absorber. The reflected component is about two orders of magnitude fainter than the primary radiation; therefore Compton thick sources are much more difficult to detect, especially at high redshift. Compton thick, reflection-dominated sources are generally characterized also by the presence of a prominent FeKα line at 6.4 keV. This line is partly produced in the accretion disk and is partly excited in the circumnuclear medium on larger scales. In Compton thin sources this iron line is heavily diluted by the direct, primary radiation, and its observed equivalent width is of a few hundred eV. In Compton thick sources the primary continuum is suppressed, and therefore the iron line emitted by the circumnuclear medium is observed with an equivalent width which easily exceeds 1 keV.

Note however that an X-ray spectrum which appear reflection-dominated, and with a prominent iron Kα line, does not necessarily imply that the source is Compton thick along our line of sight. Indeed, if the active nucleus fades, its light echo keeps the circumnuclear medium reflecting the radiation for several years, producing a reflection-dominated spectrum, even if the nucleus is totally unobscured. Compton thin to Compton thick transitions have been sometimes interpreted in terms of this "fossil" scenario (Guainazzi et al. 2002; Matt et al.

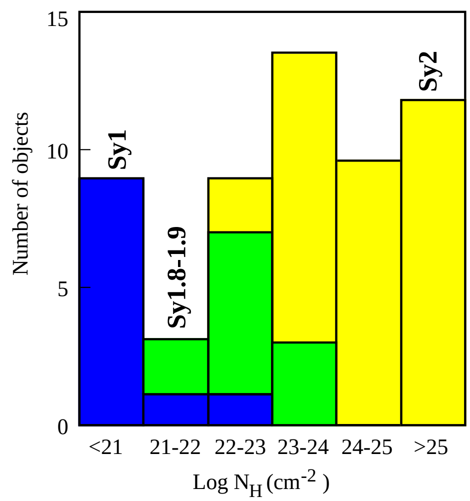

Figure 1 N_H distribution for AGN selected in [OIII]5007 line flux, divided in different optical types. Taken from Salvati & Maiolino (2000) (adapted from Risaliti et al. 1999).

2003). However, in most of these cases it is difficult to distinguish whether the spectral change is really due to an intrinsic fading of the source or to an increase of the absorbing column density (see Sect.5). Yet, in a few cases the systemic decline of the luminosity, monitored through various epochs, unambiguously identifies the Compton thick–like appearance of the final spectrum as due to the fossil nature of the source (Gilli et al. 2000).

Finally, it should be noted that absorption in the hard X-rays is due to metals, therefore what we actually is the column of metals. To infer the equivalent column of hydrogen people generally assume (explicitly or, more often, implicitly) solar abundances. However, nearly all AGNs display super-solar abundances (Hamann et al. 2002; Nagao et al. 2006a,b). As a consequence, hydrogen column densities inferred from X-ray spectra are generally overestimated.

4. The N_H distribution among AGNs

Early investigations with hard X-ray satellites clearly revealed an excess of absorption in type 2 Seyferts, in agreement with the expectations from the unified model. However, such early studies could identify only very few Compton thick sources, suggesting that the latter is a very rare class of objects. Yet, later, deeper surveys, adopting careful selection criteria and exploiting a wider energy range, discovered a much larger fraction of Compton thick AGNs (Maiolino et al. 1998; Bassani et al. 1999). By extracting a subsample selected in [OIII]λ5007 flux, assumed to trace the intrinsic AGN flux, Risaliti et al. (1999) could determine a first, unbiased distribution of N_H among Seyfert nuclei (Fig.1). Among optically obscured Seyfert nuclei the distribution of N_H is nearly flat, and Compton thick Seyfert 2s ($N_H > 10^{24}$ cm^{-2}) are found to be as numerous as Compton thin ones. Generally there is a good correspondence between optical classification and X-ray absorption: Sy1s tend to have little or no absorption, "strict" type 2 Seyferts tend to be heavily absorbed ($N_H > 10^{23}$ cm^{-2}), while intermediate type 1.8–1.9 Seyferts are absorbed by intermediate N_H ($\sim 10^{22} - 10^{23}$ cm^{-2}).

The column density distribution has been extracted also for other samples of AGNs selected in different ways. Markwardt et al. (2005) and Bassani et al. (2006) give the N_H distribution of AGNs selected in the 10–100 keV energy range. These samples are less biased against obscured AGNs, with respect to samples selected at lower energies, but they are still biased against Compton thick AGNs. Indeed, as discussed above, AGNs with $N_H > 10^{25}$ cm^{-2} are absorbed at all energies, while partially Compton thick AGNs with $10^{24} < N_H < 10^{25}$ cm^{-2} do show a transmitted component at E>10 keV, but still significantly absorbed with respect to Compton thin AGNs. Indeed, the samples presented by Markwardt et al. (2005) and Bassani et al. (2006) show the absence of AGNs with $N_H > 10^{25}$ cm^{-2} and a paucity of AGNs with $10^{24} < N_H < 10^{25}$ cm^{-2}.

Radio emission is another selection which should be free of absorption biases. Indeed, early X-ray studies of radio-loud AGNs revealed a large fraction of obscured AGNs (Sambruna et al. 1999). The absorbing column density is also found to anti-correlate with the radio core dominance parameter R (a measure of the jet orientation), in agreement with the expectations from the unified model (Grandi et al. 2006). However, there is a puzzling shortage of Compton thick AGNs, which is confirmed also in more recent studies (Evans et al. 2006; Hardcastle et al. 2006). A possible explanation is that the radio jet contributes (or dominates) the X-ray luminosity, which is therefore inefficiently obscured by a compact, circumnuclear medium.

Recently, Cappi et al. (2006) measured the column density with XMM in a distance limited sample of Seyferts (pre-selected through optical spectroscopy, Ho et al. 1997). Within the statistical uncertainties, the resulting N_H distribution is similar to that obtained in previous optically selected samples.

One of the major limitations of the previous surveys is that in most of them AGNs were pre-selected to have a Seyfert-like optical spectrum. However, hard X-ray observations (Vignati et al. 1999; Guainazzi et al. 2000; Della Ceca et al. 2002) have revealed the presence of heavily obscured, relatively luminous Seyfert nuclei ($L_{2-10\ \mathrm{keV}} > 10^{42}$ erg s^{-1}) in galaxies optically classified as starburst (HII) or LINER (here with the latter term we refer to emission due to shocks in starburst superwinds, not nuclear LINERs). Similar results have been obtained through near- and mid-IR spectroscopy (Imanishi et al. 2006; Risaliti et al. 2006). Maiolino et al. (2003) investigated the statistical properties of such optically elusive Seyfert nuclei, and found that most of them are Compton thick. Therefore, the actual fraction of Compton thick AGNs is higher than inferred in samples where objects are pre-selected through the optical spectrum. Note that evidence for relatively powerful Seyfert nuclei hosted in galaxies which are apparently normal in the optical has also been found in high redshift surveys (e.g. Comastri et al. 2002; Szokoly et al. 2004; Barger et al. 2005; Cocchia et al. 2007). However, in several of these cases the optical mis-classification may simply be due to dilution of the nuclear light by the host galaxy (Moran et al. 2002) or to inappropriate (rest-frame) spectral coverage (Severgnini et al. 2003).

5. The location of the cold X-ray absorber

Location, size and geometry of the absorbing medium have been some of the most debated topics. Although somewhat artificially, the gaseous, X-ray absorber can

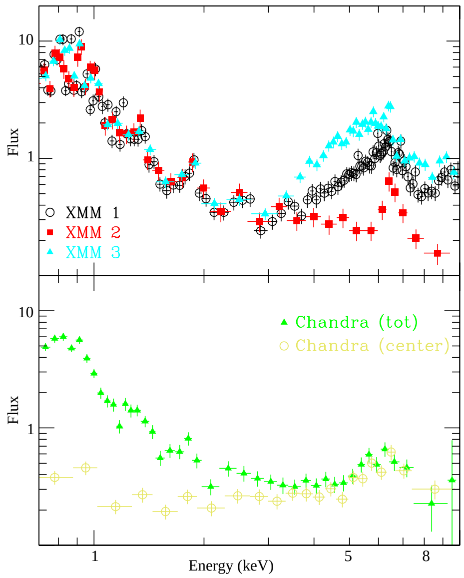

Figure 2 Unfolded spectra of NGC 1365 taken during a period of about 8 months showing strong N_H variations (from Risaliti et al. 2005). The most rapid variation is observed between observations XMM1 and XMM2, which are only three weeks apart, and which show a transition from Compton thin to Compton thick.

be roughly divided in two main components: an extended medium (on scales of 10–100 pc) and a compact, nuclear absorber (<1–10 pc).

Evidence for an absorbing medium on scales of about 100 pc, possibly associated with the host galaxy gaseous disk, has been inferred from the statistical properties of the hosts and of the NLR of Seyfert galaxies (e.g. Maiolino & Rieke 1995), from the direct observation of obscuring structures in high resolution images (e.g. Malkan et al. 1998) and from the detection of circumnuclear molecular gas (e.g. Schinnerer et al. 1999). The X-ray absorption properties of such large scale absorbers have been studied with some detail by Guainazzi et al. (2005). They found that Seyfert nuclei with dusty structures, observed within the central few 100 pc in HST images, are typically characterized by an absorbed, but Compton thin X-ray spectrum.

Evidence for an additional, much more compact gaseous absorber is directly obtained from X-ray data. There are two lines of evidence, one based on dynamical mass constraints and the other one on time variability.

Risaliti et al. (1999) showed that, for any reasonable geometry, gas with $N_H > 10^{24}$ cm^{-2} cannot be accommodated on scales larger than a few 10 pc without exceeding the dynamical mass in the same region. Therefore, the Compton thick medium must be located within the central ~10 pc.

Tighter constraints come from the observed temporal variability of the absorbing column density. Risaliti et al. (2002) showed that variability of the X-ray absorbing column density on time scales of years is observed in nearly all AGNs for which multi-epoch X-ray observations are available. For a subsample of the sources variability is observed even on scale shorter than one year. For any reasonable geometry of the individual clouds, the latter result implies that in these sources most of the the X-ray absorption must occur on sub-parsec scales. Even tighter constraints come from dedicated X-ray monitoring of some individual sources (Risaliti et al. 2005; Elvis et al. 2004). These observations revealed strong N_H variations, by even passing from the Compton thin to the Compton

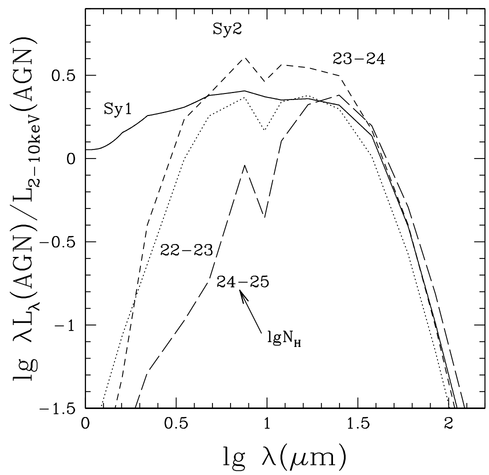

Figure 3 Nuclear, infrared spectral energy distribution observed in local AGNs, averaged in bins of absorbing N_H inferred from the X-rays. The IR SEDs are normalized to the absorption-corrected, hard X-ray luminosity. There is little variation of the nuclear IR SED for different values of N_H, except for Compton thick sources, which show a significant depression short-ward of 10μm.

thick regime, on time scales of weeks or even as short as a few hours (Fig.2). These rapid variations indicate that the absorber must much closer to the source than the standard pc-scale model, and probably co-spatial with the Broad Line Region. Further results and details on the variability of X-ray absorption are given in the contribution by Risaliti within these conference proceedings.

6. X-ray absorption versus optical and infrared absorption

Various studies have shown that X-ray and optical nuclear absorption do not match in AGNs. In particular, the measured optical dust extinction is systematically lower than inferred from the column density N_H measured in the X-rays, assuming a Galactic gas-to-dust ratio (Maiolino et al. 2001a). An important consequence of this effect is the mismatch between optical and X-ray classification, and in particular the existence of type 1, broad line AGN with significant X-ray absorption (Wilkes et al. 2002; Hall et al. 2006; Szokoly et al. 2004; Barger et al. 2005; Fiore et al. 2003; Silverman et al. 2005). Extreme cases of this kind of mismatch are Broad Absorption Line (BAL) QSOs whose X-ray spectrum is heavily absorbed, and in some cases even Compton thick, although their optical spectrum shows little or no dust extinction (Gallagher et al. 2006; Braito et al. 2004; Maiolino et al. 2001c).

For what concerns the origin the mismatch between X-ray and optical absorption, there are two possible physical reasons. The BLR is dust free, because inside the dust sublimation radius; therefore, if a large fraction of the X-ray absorbing column density is located within the BLR, as discussed in the previous section, then this naturally yields to a reduced A_V/N_H. Additionally, the circumnuclear dusty medium of AGNs is very dense (n $\sim 10^5$ cm^{-3}) and in such dense environments dust grains tend to be larger, therefore being less effective in absorbing the optical and UV radiation (Maiolino et al. 2001b).

Similar results have been obtained from the comparison between infrared and X-ray absorption. By using Spitzer mid-IR spectra, Shi et al. (2006) found that the depth of the dust silicate feature at ~ 9.7 μm correlates with the X-ray absorption, though with a large scatter. However, in most cases the silicate feature is much shallower than expected from the N_H inferred from the X-rays by assuming a Galactic gas-to-dust ratio. Also the intensity and shape of the mid-IR continuum are little related by the presence of X-ray absorption along the line of sight. More specifically, Silva et al. (2004) found that the shape and intensity of nuclear mid-IR continuum of AGNs is essentially unchanged and independent of the column density N_H measured in the X-rays (Fig.3). Only for Compton thick sources the mid-IR SED appears reddened at wavelengths shorter than $\sim 10\mu m$, but the inferred extinction is still more than one order of magnitude lower than expected from the N_H inferred from the X-rays. Similar results were obtained by Lutz et al. (2004) and Krabbe et al. (2001). The motivations for the reduced IR absorption relative to the X-ray absorption are partly the same as for the case of the optical absorption. However, an important additional factor contributing IR/X-ray absorption mismatch is that the mid-IR emission is extended, at least on the pc-scale, i.e. on a scale comparable or larger than the dense X-ray absorbing medium.

7. X-ray absorption at high luminosities and at high redshift

Until a few years ago the existence of obscured QSOs (QSO2s) was under question. QSO2s are difficult to find because both absorbed and rare. However, recently a large number of QSO2s have been found in by systemic surveys over large sky areas, in the optical (Zakamska et al. 2003; Ptak et al. 2006), in the X-rays (Norman et al. 2002; Fiore et al. 2003; Barger et al. 2005; Silverman et al. 2005; Maccacaro et al. 2004; Maiolino et al. 2006), in the radio (Donley et al. 2005; Belsole et al. 2006) and in the infrared (Martínez-Sansigre et al. 2005; Polletta et al. 2006; Alonso-Herrero et al. 2006; Franceschini et al. 2005).

The large number of newly discovered QSO2s has allowed the investigation of the fraction of obscured AGNs as a function of luminosity. By using the results from hard X-ray surveys, various authors have found evidence for a decreasing fraction of obscured AGNs with increasing luminosity (Ueda et al. 2003; La Franca et al. 2005; Barger et al. 2005; Akylas et al. 2006), although this result has been questioned (Dwelly & Page 2006). The same trend was found by Simpson (2005) among optically selected AGNs. If confirmed, these results can be interpreted within the scenario of the so-called “receding torus” (Lawrence 1991), where the dependence of the dust sublimation radius with luminosity causes the covering factor of the absorbing medium to decrease with luminosity. Alternatively, Lamastra et al. (2006) suggested that the dependence of the covering factor with luminosity is an indirect consequence of the gravitational effects of the black holes, which is on average more massive in more luminous AGNs, because of selection effects.

One should keep in mind that, at least in hard X-ray surveys, the census is limited to the Compton thin sources. Indeed, the faintness of Compton thick AGNs even in the hard X-rays prevents their detection at cosmological distances (except for a tail of the population, Tozzi et al. 2006). To infer the fraction of Compton thick sources at high redshift we have to rely on other, indirect indicators. One possibility is to exploit the shape of the hard X-ray background. Gilli et al. (2006) show that the population of (Compton thin) AGNs that resolve the X-ray background at 2–10 keV fall short to account for the peak of the latter at 30 keV. The additional contribution by a population of Compton thick AGNs with $10^{24} < N_H < 10^{25}$ cm^{-2} is required to match the shape and intensity of the X-ray background at energies higher than 10 keV. The required proportion of Compton thick AGNs with $10^{24} < N_H < 10^{25}$ cm^{-2} relative to Compton thin AGNs must be 1:2, i.e. as observed in local AGNs. Note however, that the X-ray background is insensitive to the population of totally Compton thick AGNs with $N_H > 10^{25}$ cm^{-2} (since their emission is totally suppressed at any energies), which therefore remains unconstrained.

An alternative method to identify Compton thick AGNs at high redshift is by means of mid-IR data. Indeed, recent Spitzer observations have discovered a large population of high-z AGNs (identified through a mid-IR, AGN-like excess) that do not have hard-X counterpart even in deep X-ray observations, and therefore are likely Compton thick AGNs (Alonso-Herrero et al. 2006; Polletta et al. 2006; Donley et al. 2005). Many of the Spitzer studies on high-z AGNs are still ongoing, therefore this field is currently in continuous evolution. However, results published so far suggest that the Compton thick AGNs at high-z (including those with $N_H > 10^{25}$ cm^{-2}) are as numerous as Compton thin AGNs, i.e. matching the same relative fractions observed in the local universe.

8. Open issues

The physical and statistical properties of the X-ray absorber in AGNs are far from being fully understood, and several questions remain unanswered yet.

We have shown that there is clear evidence for a compact absorber, located on the scale of the BLR, in a few sources. However, it is not clear whether such a compact absorber is ubiquitous to *all* AGNs or not. A related issue is whether *all* AGNs have Compton thick gas around them (including those which are Compton thin along our line of sight) or not. For what concerns the structure of the absorber, it is not clear yet whether the temporal variations of N_H are tracing a medium with two phases (cold, dense clouds inside a warm medium), or a more homogeneous, cold gas with density gradients. In terms of stability of the X-ray absorber, it is not clear how its vertical structure (required to account for the large covering factor) is supported.

Another class of issues is related to some puzzling comparisons of the X-ray absorption with other observed quantities. Zhang et al. (2006) found that AGNs with nuclear H_2O maser disks are not preferentially Compton thick. However, the detection of maser emission requires large columns of gas ($N_H > 10^{23-24}$cm^{-2}) and very small disk inclination ($< 10°$), the combination of which are expected to produce Compton thick absorption, that instead is observed for only half of the AGNs in the maser sample of Zhang et al. (2006) (i.e. the same fraction observed in optical samples). On the large scales there is an opposite issue. Maiolino et al. (1999) found that the X-ray absorption is correlated with the presence of a bar in the host galaxy. In particular, Compton thick AGNs appears preferentially hosted in barred galaxies. As discussed above, Compton thick absorption probably occurs on the sub-parsec scale, therefore it is hard to understand how the physics of the sub-parsec medium can be affected by the dynamical properties of the host galaxies on the kpc scale. We have verified

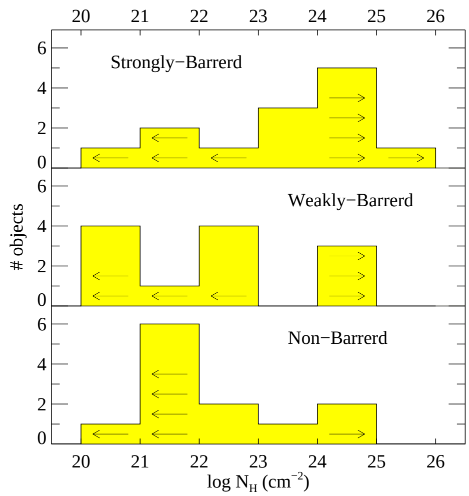

Figure 4 Column density distribution of the sources in the samples of Cappi et al. (2006) and Guainazzi et al. (2005), divided as a function of the strength of the stellar bar in the host galaxy. There is a significant progression of the average N_H as a function of the bar strength. In particular, most Compton thick nuclei are hosted in barred galaxies.

the Maiolino et al. (1999) result by using the more recent data by Cappi et al. (2006) and Guainazzi et al. (2005); but even in these samples the correlation remains, as illustrated in Fig.4.

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