On the nature of the X-ray absorption in Seyfert 2 galaxies

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\textbf{ABSTRACT}

We have studied the correlation among X-ray absorption, optical reddening and nuclear dust morphology in Seyfert 2 galaxies. Two main conclusions emerge: a) the Balmer decrement and the amount of X-ray absorption are anticorrelated on a wide range of column density: $10^{21} \lesssim N_H \lesssim 10^{24}\text{ cm}^{-2}$. The correlation does no longer apply to Compton-thick objects ($N_H \gtrsim 10^{24}\text{ cm}^{-2}$), although they span a comparable range in Balmer decrement; b) Compton-thin Seyfert 2s seem to prefer nuclear environments, which are rich of dust on scales of the hundreds parsecs. On the other hand, Compton-thick Seyferts exhibit indifferently “dust-poor” and “dust-rich” environments. These results support an extension of the Seyfert unification scenario (as recently proposed by Matt, 2000), where Compton-thick Seyfert 2s are observed through compact “torii”, whereas Compton-thin ones are obscured by dust on much larger scales.

\textbf{Key words:} Galaxies:active – Galaxies:Seyfert – Galaxies:ISM – Galaxies:nuclei – X-rays:galaxies

1 INTRODUCTION

The nuclear X-ray emission of most Seyfert 2 galaxies is seen through substantial amount of neutral absorbing matter (Awaki et al. 1991; Turner et al. 1997). This is in good agreement with the predictions of the “Seyfert unified theories” (Antonucci & Miller 1985; Antonucci 1993), which were originally invoked to explain the broad optical lines emerging in the spectropolarimetric observations of NGC 1068 (Antonucci & Miller 1985) and of several other Seyfert 2s (Tran 1995; Heisler et al. 1997). These theories postulate that Seyfert 2 nuclei are seen through a dusty molecular torus, which surrounds the nuclear environment on scales of the order of about 1 pc. Even those few cases, where no X-ray absorption is measured, can be easily reconciled with this scenario. The very flat X-ray spectra and huge fluorescent iron lines suggest that the nucleus is completely hidden in the 2–10 keV and that the nuclear radiation is seen via reflection or electron scattering (Matt et al. 1996a). Well known examples of this phenomenology are Circinus Galaxy (Matt et al. 1999), and NGC 6240 (Vignati et al. 1999). It is straightforward to interpret these components as the direct view of the nuclear emission, which is mirrored in the 2–10 keV band.

In this paper, following the most common nomenclature, we will refer to the above classes of Seyfert 2s as Compton-thin and Compton-thick, respectively.

According to the unification scenario, the difference between Compton-thin and -thick objects is mainly in the value of the column density, $N_H$. If it exceeds $\lesssim 10^{24}\text{ cm}^{-2}$, the matter becomes thick to Compton scattering, the impinging photons are down scattered to energies where the photoabsorption cross section is dominant, the nuclear radiation is totally suppressed and we observe a Compton-thick object. If the column density has lower values (either because the matter is less dense or due to a shorter optical path to the observer), part of the incoming radiation can be transmitted through the absorbing cloud(s).

Two recent papers provide for the first time a conspicuous basis to study the X-ray properties of a sizable sample of Seyfert 2 galaxies and their correlation with their multwavellength spectral energy distribution and nuclear morphology. Bassani et al. (1999, B99) have recently collected all the Seyfert 1.8 to 2s, for which reliable hard X-
ray spectra are available, and listed the corresponding absorbing column densities, together with [O\textsc{iii}] luminosities and Balmer decrements. This catalogue makes use of all the available X-ray spectroscopic measurements up to ASCA and BeppoSAX to discriminate between nuclear transmitted and scattered or diffuse emission. It should therefore allow a statistically robust identification of the proper absorbing column density towards the nucleus. By construction, this sample is not unbiased, the main potential selection effect being against obscured objects at the faintest fluxes. Risaliti et al. (1999), however, suggest that such a bias can be strongly reduced if only sources with an [O\textsc{iii}] flux higher than \(3 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\) are considered. Underlying this statement, it is assumed that the [O\textsc{iii}] luminosity is a good (i.e.: within a factor of a few) estimator of the intrinsic nuclear power (Maiolino et al. 1998).

On the other hand, Malkan et al. (1998, M98) carried out a systematic skew survey of a sizable sample of nearby galaxies with the WFC2 on board the \textit{Hubble Space Telescope} (HST), aiming at studying the nuclear morphology in Seyfert 1, Seyfert 2 and \textit{Hii} galaxies. Their images unveiled a plethora of complex structures on scales of the hundreds of parsecs, both in emission and in absorption. A summary of their findings and classification is given in Sect. 2.

### 1.1 The scope of the paper and its current observational context

In this paper we aim at studying the correlation between X-ray absorption, optical reddening and nuclear dust morphology. Our results suggest that the absorbing matter in Compton-thick and -thin Seyfert 2s is associated with different physical regions or geometries, and propose that a correlation with the absorption structures seen by the HST/WFPC2 may exist in Compton-thin Seyferts only. The interpretation of the results must take into account the limitations of the X-ray instruments, whose measurements have been employed to build up the B99 catalogue. At the level of spatial resolution (\(\sim\) arcminutes) of such detectors in the 2–10 keV energy band, one needs to assume that the bulk of the observed X-rays comes from a region very close to a nuclear engine powered by accretion onto a supermassive black hole. The column density derived from the spectral fits provides an integrated measurement of the amount of absorbing matter along the line of sight, which we associate with a geometrically thin, possibly not homogeneous screen. If the X-ray emission is due to the superposition of different components, emitted by gas at different scales/distances from the active nucleus, the integrated spectrum could be misleading. Moreover, each of these components could be differently absorbed. Even if the absorption structure along the line of sight is known, little can in principle be said on the extent and distribution of the gas along different viewing angles, and mostly from variability arguments (see, e.g., Guainazzi et al. 2000).

However, a nuclear origin for the bulk of the X-ray emission above 2 keV in Compton-thin Seyfert 2 galaxies can hardly be challenged. Their X-ray luminosity (Smith & Done 1996; Turner et al. 1997), variability properties (see, e.g., Guainazzi et al. 1998), and the very presence of nuclear point-like sources in the ROSAT images (alongside with extended emission in a few objects; cf. Matt et al. 1994; Morse et al. 1995; Weaver et al. 1995; Rush & Malkan 1996) strongly support the existence of a dominating nuclear source, seen either in transmission, through scattering, or both. The discovery of transmitted, highly absorbed components above 10 keV in a few scattering-dominated Seyfert 2s provides a strong observational support for the application of the same idea to Compton-thick objects as well. The first results provided by the \textit{Chandra} observatory (whose payload allows X-ray imaging with an unprecedented spatial resolution of \(\sim 0.5^\prime\)) broadly support the same scenario. Most of the emission in Mkn 3 (Sako et al. 2000) and the Circinus Galaxy (Samo nova et al. 2001) is concentrated in an unresolved source, coincident with the active nucleus. In the Circinus Galaxy the upper limit on the size of the unresolved emitting region is \(\sim 15\) pc only. Its spectral properties are very close to those observed by ASCA (Matt et al. 1996) or BeppoSAX (Matt et al. 1999; Guainazzi et al. 1999). This unresolved component is often embedded in diffuse gas, whose contribution to the total emission substantially decreases with energy. Conversely, only diffuse emission (on scales \(\sim 165\) pc) is observed in NGC 1068 (Young et al. 2001), where the column density to the nucleus is likely to exceed \(10^{23} \text{ cm}^{-2}\) (Matt et al. 1997), and therefore no transmission through the absorber is expected. Although these data are opening new exciting perspectives to the study of the distribution of matter in the nuclear region of nearby Seyfert 2s, they do not contradict the scenario depicted before the advent of \textit{Chandra}, and which is assumed throughout this paper.

The paper is organized as follows. Sect. 2 briefly summarizes the M98 sample properties. In Sect. 3, we present the “Balmer Decrement versus X-ray absorption” plane. The correlation of the M98 nuclear morphology classes with several others physical and morphological observables is discussed in Sect. 4. In Sect. 5 and 6 we briefly discuss some implications of our findings. The main results of this paper are summarized in Sect. 7.

### 2 THE NUCLEAR MORPHOLOGY SAMPLE

The sample of M98 contains 256 of the nearest (\(z < 0.04\), see Fig. 2) Seyfert 1s (91), Seyfert 2s (114) and starburst galaxies (51). For each galaxy images with the F606W filter on the WFC2 on board the HST were taken, which has a mean wavelength of 5940Å and a Full Width Half Maximum of 1500Å. The plate scale of 0′′.046 per pixel corresponds to 130 pc for the farthest object. A wealth of different structures are seen in these images, both in emission (bars, rings, filaments/wisps) and in absorption (dust lanes and patches). Without entering in the details of the classification (which is admittedly qualitative and partly subjective) the most relevant result to our paper is that Seyfert 2 galaxies are significantly more likely to exhibit dusty nuclear environments (see, however, Antonucci 1999 for a different view). M98 speculate that “this galactic dust could produce much of the absorption in Seyfert 2 nuclei which had instead been attributed to a thick dusty accretion torus forming the outer part of the central engine” and elaborate an alternative model to account for the observed absorption in term of galactic dust (Galactic Dust Model, GDM). Given the size of the M98 sample and the need for homogeneous experi-
Figure 1. Redshift distribution of the Malkan et al. (1998) sample. Only objects for which measures of both O\,[iii] and FIR luminosity are available, allowing direct comparison with Figures 3 and 4.

The X-ray absorption versus Balmer decrement plane

In Fig. 2 we plot the Balmer Decrement (BD) versus the X-ray absorption column density for a sub-sample of Seyfert 2s extracted from the B99 catalog. The sub-sample includes only: a) objects whose redshift is <0.04, to be consistent with the M98 sample; b) objects with \( f_{[OIII]} > 4 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \), as suggested by Risaliti et al. (1999) to ensure the completeness of the B99 sub-sample.

The plot is rather complex and exhibits some interesting features. Let’s consider first the Compton-thin sources. A strong anticorrelation between Balmer decrement and \( N_H \) is evident. The linear correlation coefficient is -0.64 for 19 objects, corresponding to a chance occurrence likelihood \( < 0.5\% \). The dotted lines in Fig. 2 represent the loci of the plain delimited by the linear best-fit to the Compton-thin data points, when the 95% statistical uncertainties on the best-fit parameters are taken into account. The widest deviations from the correlation are represented by two objects with high Balmer decrement and high \( N_H \) (Mkn 273 and NGC 5194), and NGC 2992, which exhibits an X-ray absorption about one order of magnitude lower than expected on the basis of its Balmer decrement. In the former case, the available measures of X-ray absorption are poorly constrained and consistent with the correlation. On the other hand, NGC 2992 exhibits secular variations of the X-ray flux by a factor up to 20 (Weaver et al. 1996; Gilli et al. 2000). It may well be that such a peculiar behavior affects the long-term properties of the nuclear emission of this objects in other wavelengths.

This anticorrelation, whatever is its origin, is not valid for the Compton-thick objects. They span the same range of Balmer decrement values as the Compton-thin ones, while, according to the above anticorrelation, they should lie preferentially at much lower values than the lowest abscissa value in Fig. 2. For instance, the Circinus Galaxy and NGC 6240 (among the first Compton-thick Seyfert 2s, whose column density has been reliably measured; Matt et al. 1999; Vignati et al. 1999), have a value of \( N_H \) three orders of magnitude higher than expected from the Balmer decrement versus \( N_H \) correlation valid for the Compton-thin objects.

The same plot as in Fig. 2 is shown in Fig. 3 for the Seyfert 2s only, which have been observed by M98. The M98 classification is reported (eventually replicated with superimposed markers if more than one structure is present simultaneously). An eye inspection of Fig. 3 seems to suggest that galaxies whose nuclear environment is dust-rich are more likely to be found in the Compton-thin half-plane, while dust-poor ones are more common in the Compton-thick half-plane. This hypothesis is investigated quantitatively in Fig. 4 where the distribution function of the M98 morphology classes is reported for Compton-thin and -thick objects separately. The ratio of dust-rich versus dust-poor

\* We remind here that the nuclear features classified by M98 are not mutually exclusive. A galaxy can exhibit simultaneously, for instance, dust lanes and emitting filaments.
The evidence for a systematic difference in the nuclear dust content between Compton-thick and -thin Seyfert 2s is still marginal, we have tried to correlate the M98 morphology classes with several intrinsic nuclear power and/or reprocessing indicators. Some results of this study are shown in Fig. 5. The IR fluxes are taken from the NED on-line archive. The FIR is defined as a linear combination of 60 and 100μm luminosities after David et al. (1992). No significant difference between the FIR distribution functions is observed on the basis of the nuclear dust content. In vain we searched also for correlations between the nuclear dust morphology and the host galaxy morphology or the core 5 GHz radio power (the plots of the corresponding distribution functions are not shown). However, “dust-poor” objects seem to correspond on average to intrinsically more active objects, the average of the [Oiii] luminosity being three times higher than in “dust-rich” objects [1.2±0.3 versus (0.42±0.10) × 10^42 erg s⁻¹]. Again, future enlargements of the sample, for which a classification of the nuclear dust morphology is available, would be of the uppermost importance to confirm this hint.

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4 CORRELATION WITH THE NUCLEAR DUST MORPHOLOGY CLASSES

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5 THE ANTICORRELATION BETWEEN BALMER DECREMENT AND X-RAY ABSORPTION

Our analysis shows that the X-ray absorbing column density and the Balmer Decrement are anti-correlated in Seyfert 2S along the whole range of N_H between 10^{21} and 10^{23} cm⁻². Fig. 6 and 7 suggest that the higher the X-ray column density, the lower the amount of reddening of the optical lines. The latter is a sensitive measure of the amount of dust-driven extinction. The intrinsic spectrum of hydrogen recombination lines is well known, for the conditions typical of the low-density Narrow Line Regions (NLR), and the derived optical extinction is not strongly dependent on the exact extinction law adopted. That dust is a common ingredient of NLR has been suggested by several studies (MacAlpine 1985; Osterbrock 1989). Netzer & Laor (1993) suggested that the apparent lower covering fraction of the NLR than the Broad Line Regions (BLR), the “emission gap” between NLR and BLR and the scaling of the BLR size with luminosity (R_{BLR} ∝ L^{1/2}) may be all explained if dust is embedded in the line emitting gas, and the BLR is located

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within the sublimation radius. The correlation in Fig. 2 and Fig. 3 is therefore likely to be telling us something about the physical structure and spatial distribution of the matter responsible for the non-stellar ionization-driven emission lines.

The observed anticorrelation between Balmer decrement and N$_{H}$ implies that the higher the amount of X-ray absorption, the more dust-free the absorbing matter is. We suggest two possible interpretations. First, let’s suppose that the matter responsible for the X-ray and optical obscuration is the same. Given a constant amount of mass available for nuclear absorption, distributed in an spherical shell, the observed N$_{H}$ scales as the inverse square of the inner side of the shell. Otherwise stated, the higher N$_{H}$, the longer the integration path, the closer to the center one goes, and consequently the brighter the ionizing continuum is seen by the obscuring matter, thanks both to the lower distance from the nuclear source and to the lower absorption of the interposed obscuring layers. The absorbing matter could hence extend towards the center up to radius where the dust is significantly sublimated and therefore not contribute substantially to the optical reddening of the narrow lines. The sublimation radius is $\sim 0.02L_{45}^{1/2}$ pc, where $L_{45}$ is the nuclear luminosity in units of $10^{45}$ erg s$^{-1}$ (Laor & Drain 1993). This is very close to the magnitude and luminosity scaling of the BLR radius (Netzer 1990; Clavel et al. 1991; Peterson et al. 1991). Such an evidence suggests that the BLR is actually mostly dust-free. This scenario, however, leaves unexplained why the properties of the absorbing matter on sub-parsec scales are connected with the NLR on two order of magnitude larger scales (Axon et al. 1997).

Alternatively, the optical and X-ray absorbing media may be totally decoupled, and the X-ray absorber may almost dust-free and/or located more innermost than the NLR (the latter hypothesis is in agreement with the unification scenario, and observationally supported in the Circinus Galaxy; Oliva et al. 1994; Matt et al. 1999). The optical reddening might be due to more external matter, associated for example either with the galactic disk or with the dusty structures seen in M98 images. The observed correlation might imply an “evolutionary correlation” between these two media, in the sense that higher-N$_{H}$ X-ray absorbing matter could by yielded through depletion of the nuclear environment dust, therefore yielding indirectly a lower reddening of the optical lines. It is admittedly not straightforward to envisage a physical process, responsible for the “transfer” of matter from hundreds to a few pc scale. Dynamical perturbations as traced by stellar bars may play a rôle. This point is further discussed in Sect. 6.

Whatever the origin of such a correlation is, it is no more valid in Compton-thick objects. In most of these objects, only lower limits on the X-ray absorbing column density can be measured. However, the corresponding Balmer decrement values span basically the same range as the in Compton-thin objects, while they should cluster at very low values if the correlation were true for them as well. Again, this suggests that the optical and X-ray absorbers are totally decoupled. Moreover, this represents, as far as we know, the first observational evidence that the X-ray absorbing matter in Compton-thin and -thick objects is qualitatively different.

6 ON THE DUST MORPHOLOGY CLASSES

A possible correlation of the nuclear dust morphology classification of M98 with the amount of X-ray absorption, suggests that the “Compton-thinness” is related to the nuclear dust morphology on the hundreds of parsecs scale. The Compton-thin objects exhibit preferentially “dust-rich” nuclear environment, while the Compton-thick can indifferentely have dust-rich or dust-poor environments. In

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**Figure 5.** Left upper: distribution histogram of [Oiii] luminosities for “dust-poor” (upper panel) and “dust-rich” (lower panel) objects; Right upper: distribution histogram of FIR luminosities for “dust-poor” (upper panel) and “dust-rich” (lower panel) objects.
Compton-thick Seyfert 2s the X-ray absorption might therefore be totally decoupled from the dust content of the nuclear environment. The presence of nuclear dust is not correlated with the galaxy type or with the FIR luminosity. It corresponds to a slightly (about a factor of three) higher average [OIII] luminosity. It would be very interesting to search for a confirmation of this X-ray absorption/morphology connection. The high-throughput scientific payload on board XMM-Newton may soon provide invaluable further measurements. Despite the still marginal evidence, we don’t refrain from speculating a bit on this intriguing hypothesis.

One may suppose that Compton-thick objects are those, which indeed contain the dusty homogeneous molecular “torus”, envisaged by the Seyfert unification theories (Antonucci & Miller 1985). The innermost side of this torus would be located at distances of the order of 1 pc (or fractions, as suggested by the water maser measurements in NGC 1068, Greenhill et al. 1997). The formation history of this “standard” torus cannot be inferred from our results alone, but, irrespectively of the details, it could contribute to deplete the dust present in the nuclear environment on ~100 pc scale. Recently, Maiolino et al. (1999) pointed out that Seyfert 2s with stellar bars tend to show the highest fraction of Compton-thick objects. Bars may therefore be very efficient in driving toward the nuclei the matter, which is responsible for the bulk of the obscuration, as already suggested on theoretical basis by Barnes & Henquist (1995). Being this true, the formation of a compact torus might be related to the strength of the central gravitational potential, as suggested by the average higher [OIII] luminosity of “dust-poor” versus “dust-rich” objects. However, there is no strong evidence so far that bars are preferentially found in active nuclei (Heckman 1980; Simkin et al. 1980; Mulchaey & Regan 1997; M98) and recent high-resolution imaging observations of a small sample of Seyfert galaxies with HST rule out that nuclear bars are the primary fueling mechanism for Seyfert nuclei (Regan & Mulchaey 1999).

On the other hand, Compton-thin sources would not have the compact torus in their innermost regions and might therefore keep their nuclear environment enough “dust-rich” for this dust to be detected in the high-resolution images of M98. We stress that there is no evidence that the dust lanes seen in HST images are themselves responsible for the X-ray absorption. Significant column densities are measured not only in sources where the nucleus is covered by dust (which are actually a few), but also in objects where the nuclear environment show dust lanes and patches, which do not intercept our line of sight to the nucleus. The above correlation is therefore valid in “environmental terms”, suggesting, otherwise stated, that the X-ray absorption measured on the Earth is the superposition of several individual unresolved “clouds”, which are statistically more numerous in Seyfert 2s than in Seyfert 1.

The above results are consistent with a scenario (as the GDM), where the X-ray obscuration, that turns a Seyfert 1 into a Seyfert 2, occurs in the host galaxy on scales of the order of hundreds parsecs. This scenario has been suggested by several authors in the past (Maiolino & Rieke 1995; Mcleod & Rieke 1995; Simcoe et al. 1997; M98). Recently, Matt (2000), has elaborated an extension of the Seyfert unification models, where Compton-thick Seyfert 2s are observed through compact, thick matter with a large covering factor and close (a few tens parsecs at most) to the nucleus, while Compton-thin or intermediate Seyferts are obscured by dust lanes at larger distances. Whether these two classes, unveiled to be qualitatively different and not simply the manifestation of different values of a critical observable (N_H), are evolutionary linked in a sequential scenario, or they are created “in parallel” from the same parents, according to a hidden critical parameter (the central black hole mass?) is an open question for the models of active galaxy evolution.

7 CONCLUSIONS

In this paper, we studied the correlation between X-ray and optical absorption, the latter measured through the Balmer decrement of the narrow hydrogen recombination lines. Moreover, we extended this study by encompassing the nuclear dust morphological classification by M98. The main results of our study can be summarized as follows:

a) in Compton-thin Seyfert 2s (i.e.: those with \( N_H < 10^{24} \text{ cm}^{-2} \)), the Balmer decrement and the amount of X-ray absorption are strongly anti-correlated along three orders of magnitude in \( N_H \), the residual scattering in the correlation being easily explained with still pending uncertainties in the measure of \( N_H \) and/or in long-term variations of the nuclear flux in a few individual objects.

b) this correlation does not hold for Compton-thick objects (\( N_H \gtrsim 10^{24} \text{ cm}^{-2} \)), which span a comparable range in Balmer decrement as the Compton-thin, despite the much higher amount of X-ray absorption.

c) Compton-thin Seyfert 2s seems to prefer nuclear environments, which are rich of dust on the hundreds parsecs scale. On the other hand, Compton-thick Seyferts do not share the same behavior, exhibiting indifferently “dust-poor” and “dust-rich” environments. The statistical significance of this results is still marginal, but can be easily improved in the nearby future with an enlarging of the sample of Seyfert 2 galaxies for which both high resolution images of the nuclear regions and reliable measures of the X-ray absorbing column density are available.

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