Warm Absorbers in Active Galactic Nuclei

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Abstract. We first provide a review of the properties of warm absorbers concentrating on what we have learned from ROSAT and ASCA. This includes dusty and dust-free warm absorbers, non-X-ray emission and absorption features of warm absorbers, and the possible warm absorber interpretation of the peculiar 1.1 keV features. We then discuss facets of warm absorbers by a more detailed investigation of individual objects: In a first part, we discuss several candidates for dusty warm absorbers. In a second part, we review and extend our earlier study of a possible relation between warm absorber and CLR in NGC 4051, and confirm that both components are of different origin (the observed coronal lines are underpredicted by the models, the warm absorber is too highly ionized). We then suggest that a potential overprediction of these lines in more lowly ionized absorbers can be avoided if these warm absorbers are dusty. In a third part, we present first results of an analysis of a deep ROSAT PSPC observation of the quasar MR2251–178, the first one discovered to host a warm absorber. Finally, we summarize our scrutiny under which conditions a warm absorber could account for the dramatic spectral variability of the Narrow-line Seyfert 1 galaxy RXJ0134-4258.

1. Introduction

Warm absorbers (WAs) are an important new diagnostic of the physical conditions within the central regions of active galaxies. They have been observed in ∼50% of the well-studied Seyfert galaxies and have also been detected in quite a number of Narrow-line Seyfert 1 galaxies. So far, they revealed their existence mainly in the soft X-ray spectral region where they show up by their characteristic metal absorption edges. The study of the ionized material provides a wealth of information about the nature of the warm absorber itself, its relation to other components of the active nucleus, and the intrinsic AGN X-ray spectral shape, and leads to a better understanding of AGN in general.

The presence of an ionized absorber was first discovered based on Einstein observations of the quasar MR 2251-178 (Halpern 1984). With the improved spectral capabilities of ROSAT and ASCA, many more warm absorbers have been found and theoretical modeling of plasma under ‘warm absorber’ conditions has been pushed forward.

Below, we first provide a review on what is known on warm absorbers after the ‘ROSAT and ASCA epoch’ of observations and theoretical modeling (Sect. 2). We then discuss in more detail the possibility that several (but not all) warm absorbers contain dust (Sect. 3). In Sect. 4 we investigate the possible relation of WA and optical/UV emission line regions with focus on NGC 4051. Sect. 5 is concerned with the warm absorber in MR 2251-178. In Sect. 7 we explore whether and under which conditions a warm absorber provides an explanation for the dramatic X-ray spectral variability of RX J0134-4258.

1 e.g., MCG 6-30-15 (Nandra & Pounds 1992, Fabian et al. 1994, Otani et al. 1996b, Reynolds et al. 1997, Orr et al. 1997, and references therein), NGC 3783 (Turner et al. 1993, George et al. 1995, 1996, Krolik & Kriss 1995, Murray et al. 1995, 1996), IC 4329A (Cappi et al. 1996, Perola et al. 1999), NGC 3786 (Komossa & Fink 1997), NGC 5548 (Nandra et al. 1993, Mathur et al. 1995, 1996, Done et al. 1995), NGC 4051 (e.g., Mihara et al. 1994, McHardy et al. 1995, Guainazzi et al. 1996, Komossa & Fink 1997a, Guainazzi et al. 1998, and references therein), NGC 4151 (Weaver et al. 1994, Warwick et al. 1995, 1996), IC 4329A (Cappi et al. 1996, Perola et al. 1999), NGC 3786 (Komossa & Fink 1997), NGC 5548 (Nandra et al. 1993, Mathur et al. 1995, 1996, Done et al. 1995), NGC 3516 (Kriss et al. 1996a, Mathur et al. 1996), Mrk 290 (Turner et al. 1996), Mrk 1298 (Wang et al. 1996, 1999, Komossa & Fink 1997d, Komossa & Meerschweinchen 2000), IRAS 13349+2438 (Brandt et al. 1996, 1997, Komossa et al. 1999b, Siebert et al. 1999), IRAS 17020+4544 (Leighly et al. 1997, Komossa & Fink 1998); see Reynolds (1997) and George et al. (1998a) for a systematic study of WAs with ASCA.

2 e.g., Halpern 1984, Krolik & Kallman 1984, Netzer 1993, 1996, Krolik & Kriss 1995, Murray et al. 1995, Reynolds & Fabian 1995, Komossa & Bade 1998, Nicastro et al. 1999a.
2. Basic properties of warm absorbers: dusty WAs, dust-free WAs, peculiar 1.1 keV features

2.1. Warm absorber models and definitions

The active nucleus is thought to contain an accreting supermassive black hole (SMBH), surrounded by the putative molecular torus and two emission line regions, the broad line region (BLR) and the narrow line region (NLR). The physical properties of the two emission line regions are quite well known, since a wealth of information can be extracted from emission line intensities, line profiles, line shifts, and line variability (see Peterson 1993 for a review).

Concerning the nature and location of the warm absorber, several different models have been suggested: (i) a relation of the WA to the BLR (a high-density component of the inner BLR, a BLR confining medium, winds from bloated stars, or a matter bounded BLR component; see, e.g., Reynolds & Fabian 1995, Shields et al. 1995, Netzer 1996), (ii) an accretion disk wind (e.g., Königl & Kartje 1994, Murray et al. 1995), (iii) a relation to the torus (e.g., Reynolds 1997, Komossa & Fink 1997b), or (iv) a relation to the NLR (see, e.g., the two-component WA model of Otani et al. 1996b). The reason for the large variety of models discussed is that not all physical properties of the warm absorber (its density \( n \), column density \( N_w \), covering factor \( \eta = \omega/4\pi \), distance \( r \) from the nucleus, elemental abundances \( Z \), its velocity field, and the shape of the illuminating continuum) can be directly determined from X-ray spectral fits, but only certain combinations of these parameters, defined below.

The two most important quantities are the column density \( N_w \) and ionization parameter \( U \) of the warm absorber. \( N_w \) is given by

\[
N_w = \int n_H d x ,
\]

where \( n_H \) is the total hydrogen density, and \( x \) the thickness of the absorber. The ionization parameter \( U \) is defined as

\[
U = \frac{Q}{4\pi r^2 n_H c} .
\]

Here, \( Q \) relates to the spectral energy distribution (SED) which illuminates the warm absorber, and is the number rate of photons above the Lyman limit \( \nu_0 = 10^{15.512} \) Hz, given by

\[
Q = 4\pi \rho^2 \int_{\nu_0}^{\infty} \frac{f_\nu}{h\nu} d\nu ,
\]

where \( d \) is the distance between observer and warm absorber. The mass of the warm absorber is approximately given by

\[
M_{wa} \approx 4\pi r^2 N_w m_p \eta = 0.02 r_{16}^2 N_{22} \eta \ M_\odot ,
\]

with \( r = 10^{16} r_{16} \) cm and \( N_w = 10^{22} N_{22} \) cm\(^{-2}\).

From direct spectral fits, one first determines \( U \) and \( N_w \). If the intrinsic continuum turns out to be variable, or if there is evidence that the warm material contains dust, important constraints on the density and distance of the absorber from the nucleus can be obtained from reaction-timescale arguments, and dust survival arguments, respectively. In particular, the recombination timescale \( t_{rec} \) of a warm absorber is given by

\[
\tau_{rec} \approx \frac{1}{n_e \eta} \frac{n_i}{n_{i+1}} \frac{1}{A} \times \left( \frac{T}{10^4} \right)^x
\]

(Krolik & Kriss 1995) where \( n_i/n_{i+1} \) is the ion abundance ratio of the metal ions dominating the cooling of the gas, \( n_e \) the electron density, and the last term is the corresponding recombination rate coefficient \( \alpha_{i+1,i} \) (Shull & Van Steenberg 1982; for coefficients \( A, X \) see Aldrovandi & Pequignot 1973). Available observations locate most warm absorbers outside the bulk of the BLR.

2.2. X-ray appearance of warm absorbers

2.2.1. Dust-free warm absorbers

So far, ionized absorbers have been mainly observed at X-ray energies; therefore, most of our knowledge on this material comes from the analysis of X-ray spectra. Warm absorbers show up in the soft X-ray band by their characteristic X-ray absorption edges which are created by K-shell photoionization of highly ionized metal ions. The warm

![Fig. 1. X-ray absorption structure of a typical warm absorber. The thin solid line corresponds to the intrinsic X-ray spectrum, the thick solid line shows the spectrum after passage of the ionized absorber. The oxygen OVII and OVIII edges are marked.](image-url)
material is thought to be photoionized by emission from the central continuum source in the active nucleus (for a detailed model invoking shocks (Meier & Denmng 1997) in addition to photoionization see Contini & Viegas 1999; see also the discussion in Nicastro et al. 1999a). Its degree of ionization is higher than that of the bulk of the BLR and the gas temperature is typically of order $10^5$ K. Fig. 1 shows the X-ray spectrum of a typical warm absorber. The most prominent absorption edges are marked. In case of high covering factor of the warm absorber, X-ray emission and reflection becomes significant and will partially fill up the edges (e.g., Netzer 1993 (his Fig. 1-3), 1996).

2.2.2. Dusty warm absorbers

Warm absorbers have been mostly modeled using the codes Cloudy (Ferland 1993, Ferland et al. 1998) and ION (Netzer 1993, 1996). For several years, the ionized absorbers were assumed to be dust-free; partly because they were observed in bright, optically unreddened Seyfert 1 galaxies, and there was no necessity at all to suspect this highly ionized material to contain dust.

The situation changed with the cases of 3C 212 (Mathur 1994), IRAS 13349+2438 (Brandt et al. 1996), and NGC 3227 (Komossa & Fink 1996, 1997a): 3C 212 is a quasar with a heavily reddened optical spectrum. Its X-ray spectrum was successfully fit by several models including a powerlaw plus excess cold absorption (Elvis et al. 1994). Since other multi-wavelength observations did not indicate a cold absorber of high column density along the line of sight, Mathur (1994) suggested that the dust that reddens the optical spectrum is mixed with a warm absorber, instead. She also showed that this material can consistently account for the observed MgII UV absorption of 3C 212. In the cases of IRAS 13349 and NGC 3277 the large column density $N_{\text{opt}}$ of dusty gas inferred from optical observations is inconsistent with the one ($N_x$) derived from X-ray spectral fits in the sense that $N_x \ll N_{\text{opt}}$ (hereafter referred to as ‘$N_{\text{opt}} - N_x$ discrepancy’). The inconsistency disappears, if the dust is accompanied by ionized gas. Further candidates for dusty warm absorbers which show the same $N_{\text{opt}} - N_x$ discrepancy emerged quickly: NGC 3786, MCG 6-30-15, IRAS 17020+4544, and possibly 4C74.26 (see Tab. 1).

Warm absorber models taking into account the presence of dust were first presented by Komossa & Fink (1996, 1997a) and applied to the ROSAT X-ray spectrum of NGC 4051 (which turned out to be likely dust-free, see Sect. 4 below), followed by NGC 3227, NGC 3786 (which are well fit by dusty warm absorbers; Komossa & Fink 1997b,c), and MCG 6-30-15 (which likely possess a two-component WA one of which is dusty; Reynolds et al. 1997).

In an alternative approach, Reynolds (1997) correlated the optical depths of OVII and OVIII of a sample of Seyferts with the ‘steepness’ of the UV continuum which he took as reddening indicator. Except for two outliers, most of the objects of his sample show low reddening and weak OVII absorption, whereas four objects show the opposite (high reddening, a larger optical depth of OVII) and these latter are suggested to likely host dusty warm absorbers. No such trend is found for OVIII.

2.2.3. Peculiar 1.1 keV features

Warm absorbers have also been observed in several Narrow-line Seyfert 1 galaxies (NLSy1s hereafter; e.g., Vaughan et al. 1999, Komossa & Meerschweinchen 2000, and references therein). In addition to the ‘standard’ warm absorbers with strong edges of OVII and OVIII around 0.7-0.8 keV, peculiar absorption features have been reported around $\sim$1 keV (e.g., Brandt et al. 1994, Otani et al. 1996a, Ulrich-Demoulin & Molendi 1996, Hayashida 1997, Leightly et al. 1997, Matt 1998, Ulrich et al. 1999, Vaughan et al. 1999).

Most interpretations of these feature focussed on warm absorbers, albeit in very different ways. The suggested explanations are: (i) Non-solar metal abundances: Absorption around 1.1 keV could be due to Ne-K absorption but would require a rather peculiar abundance ratio of Ne/O for the Ne absorption to be much stronger than the O absorption. In addition, the strongest Ne edge in most models is located at 1.36 keV at somewhat higher energies.

![Fig. 2. Influence of dust mixed with the warm absorber on the X-ray absorption structure (log $U = -0.5, \log N_w = 21.6$). The straight solid line corresponds to the unabsorbed intrinsic spectrum, the heavy solid line to a dust-free warm absorber (WA) with solar abundances, the dotted line to a dust-free WA with the same depleted abundances as in the dusty model, and the long-dashed line to the change in absorption structure after adding dust to the WA (other model parameters are fixed). Clear changes in the absorption structure are revealed for the models that include dust. The abscissa brackets the ROSAT energy range (0.1-2.4 keV); some prominent edges are marked.](image-url)
than observed; Komossa & Fink 1998, Ulrich et al. 1999. Alternatively, it could be caused by Fe-L absorption (applied to PG1404+226 this requires an Fe overabundances of $>25\times$ solar; Ulrich et al. 1999). (ii) A warm absorber in relativistic outflow; the $\sim1$ keV feature is then caused by highly blueshifted OVII or OVIII edges (Leighly et al. 1997; see also Brandt et al. 1994 and Otani et al. 1996a). (iii) A sequence of resonance absorption lines in combination with a steep X-ray spectrum (Nicastro et al. 1999c).

It is important to keep in mind, though, that the observed features seem to occur always close to the position where the declining soft excess emission intersects the powerlaw component, and the possibility remains that the absorption feature is only mimicked by a more complex spectral shape. Further, in the case of Ark564 the feature is better described by an emission line than an absorption complex (Vaughan et al. 1999, Turner et al. 1999).

2.3. Relation to UV absorbers

The ‘X-rays-only’ approach to study warm absorbers suffers from the still limited spectral resolution of current X-ray detectors making measurements of, e.g., red/blueshifts of the absorption edges difficult. A powerful approach to constrain further the properties of warm absorbers is to combine the X-ray with UV observations, and to search for the signature of the warm absorbers simultaneously in both spectral regions.

The relation between UV and X-ray (cold) absorbers was examined by Ulrich (1988). Mathur and collaborators (e.g., Mathur 1994, Mathur et al. 1994, Mathur et al. 1995) then presented several good cases (3C 212, 3C351, NGC5548) where UV and X-ray warm absorber are very likely one and the same component (see also deKool & Meurs 1994 on PG 1416-129). These absorbers are outflowing with velocities of $\sim1000-3000$ km/s and are located outside the BLR. Three further good candidates for a common UV–X-ray warm absorber are the high-redshift quasar PKS 2351-154 (Schartel et al. 1997), the Sy 1 galaxy NGC 3783 (Shields & Hamann 1997), and the quasar PG 1114+445 (Mathur et al. 1998). Hamann et al. (1995a) reported the detection of NeVIII774 absorption in the quasar UM 675, and noted that this gas could act as X-ray warm absorber. Telfer et al. (1998) analyzed the very highly ionized BAL system of the quasar SBS 1542+541 and concluded that it is likely associated with an X-ray warm absorber.

Sometimes, though, the UV absorption is rather complex and shows the presence of different components with different degrees of ionization and/or velocities (e.g., NGC 3516, Kriss et al. 1996b, Crenshaw et al. 1998; NGC 5548, Mathur et al. 1999; NGC 7469, Kriss et al. 1999), and only one component (e.g., NGC 5548) or none (e.g, NGC 7469) may be identified with the X-ray warm absorber.

In any case, the near one-to-one match of the presence of UV- and X-ray warm absorbers in a sample of Seyfert 1 galaxies (Crenshaw et al. 1999) suggests a common or related origin of UV and X-ray absorbing material.

2.4. Non X-ray line emission from warm absorbers

Examples of UV-EUV lines that become strong under warm absorber conditions were given in, e.g., Krolik & Kriss 1995 (their Fig. 4), Shields et al. 1995, Netzer 1996 (his Fig. 10), and Komossa & Fink 1997d (their Fig. 6), 1997e.

Observationally, the EUV emission line NeVIII774 was detected in the spectra of high-redshift quasars (Hamann et al. 1995b,c, 1998) and was suggested to originate from a warm absorber. (X-ray spectra of these objects are not yet available for a check and more detailed modeling).

A more detailed approach then was to select individual, well observed AGN and to investigate whether the physical conditions in one of the observed optical-UV emission line regions and the X-ray warm absorbers are identical, such that the ionized X-ray absorber could be directly identified with one of the known (high-ionization) emission line regions. Mathur et al. (1994) presented detailed modeling of the BELR of the quasar 3C351 which also shows an X-ray warm absorber, and concluded that high-ionization BELR and warm absorber of 3C351 are not one and the same component. Komossa & Fink (e.g., 1997a,b) studied the cases of NGC 4051 (summarized and extended in Sect. 4 below) and NGC 3227. They first derived all warm absorber properties that can be determined from X-ray spectral fits, then varied the remaining free parameters (like metal abundances), predicted for each case the optical/UV line emission from the X-ray absorbing gas and compared with optical observations. Again, they concluded that warm absorber and CLR in NGC 4051, and WA and emission-line components in NGC 3227 show different physical conditions. Reynolds et al. (1997) followed a similar approach in application to MGC 6-30-15 and find that [FeX] and [FeXIV] could be explained by an (outer) warm absorber of covering factor $\sim0.08$, but that this would heavily underpredict the observed [FeXI] emission. Contini & Viegas (1999) presented a detailed multi-cloud model in which both, photoionization and shocks contribute to the heating and ionization of the clouds, and applied their model to NGC 4051. They find that the observed X-ray spectrum and the NLR line emission can be successfully reproduced by an ensemble of clouds of different densities. [Predicted emission line intensities for coronal lines have not yet been reported.]

3. Dusty warm absorbers

Below, we describe in more detail the properties of dusty warm material, and provide a summary of the suggested candidates for dusty WAs including explicit spectral model fits.
Table 1. Summary of the candidates for dusty warm absorbers, listed in the chronological order they were suggested. The column “ sug.” gives those references that proposed the presence of a dusty warm absorber, whereas the column “mod.” lists the works that first modelled the X-ray data in terms of a dusty warm absorber. Values of the ionization parameter $U$ (Eq. 2) given here and elsewhere in the text refer to a continuum spectrum with $\alpha_{\text{EUV}} = -1.4$ (between Lyman-limit and 0.1 keV) and $\Gamma_x$ as listed.

| object       | type        | warm absorber fit $\Gamma_x^{\text{inst}}$ | references | comments               |
|--------------|-------------|---------------------------------------------|------------|------------------------|
| 3C 212       | ‘red’ quasar| $-2.4$ $-0.5$ $21.9$                        | [1]        | dusty WA not yet fit   |
| df           |             |                                             |            | best-fit parameters of dust-free WA |
| IRAS 13349+2438 | NL quasar | $-2.9$ $-0.4$ $21.2^1$                      | [2], [3], [10], [11] |                         |
| df           |             |                                             |            | dust-free WA for comparison |
| NGC 3227     | Sy 1.5      | $-1.9$ $-0.3$ $21.8$                        | [4], [5], [4] |                         |
| NGC 3786     | Sy 1.8      | $-1.9$ $-0.8$ $21.7$                        | [6]        |                         |
| MCG 6-30-15  | Sy 1        | $-2.2$ $0.7$ $22.7$                        | [7]        |                         |
| IRAS 17020+4544 | NLSy 1 | $-2.8$ $0.7$ $21.6^1$                      | [8], [12] | (>)-2-comp. WA |
| sil          |             |                                             |            |                         |
| 4C +74.26    | radio quasar| $-2.2$ $-0.1$ $21.6$                        | [9], [9]   |                         |
|              |             |                                             |            | excess cold absorption possible |

1) fixed to the value $N_{\text{opt}}$ determined from optical reddening. References: [1] Mathur 1994, [2,3] Brandt et al. 1996, 1997, [4] Komossa & Fink 1997b (see also Komossa & Fink 1996), [5] George et al. 1998b, [6] Komossa & Fink 1997c, [7] Reynolds et al. 1997 (the possibility of a dusty WA in this galaxy was earlier briefly mentioned in Reynolds 1997), [8] Leighly et al. 1997, [9] Komossa & Fink 1998, [10] Komossa & Greiner 1999, Komossa et al. 1999b, [11] Siebert et al. 1999, [12] Komossa & Bade 1998.

3.1. Modifications of the X-ray absorption structure

Several changes occur in the presence of dust mixed with the warm absorber: (i) Gas dust interactions influence the thermal conditions in the gas and change its ionization state (e.g., Draine & Salpeter 1979). In particular, for high ionization parameters dust effectively competes with the gas in absorbing photons (Laor & Draine 1993). (ii) Dust scatters and absorbs the incident radiation and X-ray absorption edges are created by inner-shell photoionization of metals bound in the dust (see Figs 4, 5 of Martin & Rouleau 1991).

Under the following assumptions we (Komossa & Fink 1997b, Komossa & Bade 1998) have calculated a sequence of dusty warm absorber models using Ferland’s (1993) code Cloudy: (i) The dust composition (graphite and astronomical silicate) and grain size distribution were chosen like in the Galactic diffuse interstellar medium (Mathis et al. 1977) if not mentioned otherwise, as incorporated in Cloudy, (ii) the metal abundances were depleted correspondingly (a mean of Cowie & Songaila 1986; see Ferland 1993, Baldwin et al. 1991 for details), (iii) the warm material was assumed to be of constant density and ionized by a ‘mean Seyfert’ IR to gamma-ray continuum (with $\alpha_{\text{uv-x}} = -1.4$ in the EUV).

The main consequences of the presence of dust internal to the warm absorber can be summarized as follows:

- Absorption edges in the X-ray spectrum from neutral metals bound in the dust, like a carbon CI edge (from the graphite species) and an oxygen OI edge (from silicate) are predicted. The shift in edge energy due to solid state effects (e.g., Martin 1970, Adamietz et al. 1993) is only of the order of a few eV (Greaves et al. 1984).]

- There is a stronger temperature gradient across the absorber, with more gas in a colder state. This and the previous effects lead to an effective flattening of the X-ray spectrum (Fig. 2).

- The increased sensitivity of dust to radiation pressure (e.g., Chang et al. 1987, Binette et al. 1997) likely causes the gas to outflow (if not otherwise confined) leading to temporal changes of the absorber properties. [Indeed, strong variability in X-ray count rate of factors 10-15 has been detected from the dusty-warm-absorber candidates NGC 3227 and NGC 3786 (Komossa & Fink 1997b,c).]

- The warm absorber emission in certain optical/UV lines, in particular the iron coronal lines, is much reduced because of the depletion of iron into dust grains. [This likely also alleviates the problem of the recently reported potential over-prediction of these lines from some warm absorbers; see Sect. 4 below].

3.2. Results from X-ray spectral fits: List of suggested/modelled candidates

We have investigated most suggested dusty-WA candidates with our models. We get successful X-ray spectral fits. In some cases the best-fit parameters can deviate substantially from those obtained by fitting a dust-free warm absorber, though. Table 1 gives a summary of the suggested dusty warm absorber candidates and the model results. The ionization parameters are found to be somewhat lower than those of dust-free warm absorbers, with
the exception of IRAS 17020. It is interesting to note that the dusty warm absorbers show a rather narrow range in column densities $N_w$ which differ by less than a factor $\sim 2$.

This is likely partly caused by selection effects: Firstly, X-ray warm absorbers of lower column density are difficult to detect presently, and small deviations of the Balmer decrement from the recombination value are less straightforwardly interpreted in terms of reddening. Secondly, in case of higher column density the dusty gas becomes optically thick, and the concept of the standard extinction curve can no longer be applied.

3.3. Origin of the dusty material

In case dust is mixed with the warm absorber, important constraints on its density and locations can be obtained from the requirement of dust survival: Firstly, dust is heated and destroyed by the radiation field of the central source if at distances less than $r_{ev} \approx \sqrt{L/4\pi}$ (e.g., Netzer 1990; see Laor & Draine 1993 for a dependence of this relation on grain size). Secondly, dust is heated by collisions with gas particles (e.g., Baldwin et al. 1991) to a temperature that exceeds the evaporation temperature if the gas density is high enough. Both approaches locate the dusty warm absorbers outside the BLR.

One component that suggests itself to be identified with the dusty warm absorber is an atmosphere of the molecular torus which plays an important role in unification schemes. The torus has the advantage that it is ‘known’ to be present (no need to invent a new component), and would provide a natural reservoir for dust close to the central power source (but far enough away to ensure dust survival). One is then lead to a viewing geometry such that our line of sight grazes the torus atmosphere in those Seyferts that show dusty warm absorbers (see also the discussion in Brandt et al. 1996, Reynolds 1997, and Komossa & Fink 1997b,c).

Looking at Tab. 1, one question arises immediately: the dusty warm absorbers seem to come in all types of Seyfert galaxies, which is not what would be expected in a simple viewing-geometry-scenario. The sample is still small, though, and it might be interesting to re-investigate this possibility once the dusty warm absorbers are confirmed, and further ones are known.

The other already earlier suggested dusty component of the active nucleus, and thus potential dusty warm absorber counterpart, is the dusty transition region between BLR and NLR ‘invented’ and studied by Netzer & Laor (1993). The ionization parameter of this region should show a smooth transition to that of the BLR and NLR, though; whereas the ionization parameters of warm absorbers are typically much higher.

3.4. Model uncertainties

The line of arguments in favor of dusty warm absorbers (reviewed in Sect. 2.2.2; see Brandt et al. 1996 and Komossa & Fink 1997b for many further details) relies on several assumption. Firstly, optical and X-ray observations were not performed simultaneously. Variability in the optical reddening on the timescale of years is possible in Seyferts (e.g., Goodrich 1989, 1995), but we note that for both, IRAS 17020 and IRAS 13349 optical spectra taken at many different epochs are available and they do not show evidence for changes in reddening (e.g., Siebert et al. 1999). Secondly, optical-UV and X-ray photons may not travel along the same l.o.s, and they may therefore ‘see’ different amounts of dust and gas. This would be the case if the X-rays were seen mainly in scattered light, or if there was a strong starburst contribution. Since most of the Seyferts with dusty warm absorber candidates are rapidly variable in X-rays (e.g., a factor of ~2 within 800 s and a factor ~10 within a few years in case of NGC 3227; Komossa & Fink 1997b) these two possibilities can be excluded.

As far as the modeling of dusty warm absorbers is concerned, one uncertainty is the applicability of the code Cloudy. More precisely, radiation pressure may drive strong outflows of the dusty gas. In case of large velocity gradients, the treatment of overlapping resonance lines becomes inaccurate (Ferland 1993), and the heating-cooling balance might be disturbed by expansion cooling of the gas.

Another uncertainty are the dust properties: Is the dust in Seyfert galaxies sufficiently similar to Galactic ISM-like dust (and is the latter really ‘MRN’-like in nature?)? Firstly, galactic ISM-like dust was also assumed to estimate the amount of dust from the optical spectra. Therefore, making the same assumption in modeling the X-ray data is a good starting point. Secondly, observations by ISO suggest that the dust/gas ratio in other galaxies does not deviate much from the Galactic value (e.g., Bianchi et al. 1999). Thirdly, even for other dust compositions or structures, the X-ray absorption structure would not change strongly, because the X-ray spectrum is not dominated by complex molecular transitions and solid state and chemical effects (these may have some influence on the heating-cooling balance, though), but by K-shell photoionization of metals bound in the dust.

3.5. Future perspectives

Given the presence of X-ray absorption edges of neutral dust-bound metals like the carbon edge, dusty warm absorbers, if confirmed\footnote{see, e.g., Laor & Draine 1993, and the recent review by Witt 1999} with XMM, AXAF and ASTRO-E,\footnote{Even if the dusty X-ray warm absorbers are not confirmed, this likely tells us a lot about the dust in these galaxies, which...}
will play an important role not only in probing components of the active nucleus, like the dusty torus, but also are they a very useful diagnostic of the (otherwise difficult to determine) dust properties and dust composition in other galaxies.

4. The warm absorber in NGC 4051, and the (missing) connection between WA and CLR

4.1. Introduction

Given the several good candidates for dusty warm absorbers the question emerges whether all warm absorbers contain dust. We think this is unlikely because (i) warm absorbers have also been observed in several Seyfert 1 galaxies that do not show evidence for optical reddening, and (ii) in some cases the modifications in the X-ray absorption spectrum due to the presence of dust are so strong that no successful X-ray spectral fit is possible.

Dust-free warm absorbers might contribute significantly to the emission in optical/UV iron coronal lines. In the following we shall examine in detail the warm absorber in the NLSy1 galaxy NGC 4051 with respect to the question whether this ionized material can account for the coronal lines observed in this galaxy. This is an update of our earlier work on this subject (see Komossa & Fink 1997a; KF97a hereafter).

4.2. Observed properties of NGC 4051

We first give a brief summary of previous observational properties of NGC 4051 relevant for the present study (taken from KF97): (i) To model the warm absorber and to predict its line emission, we compiled the observed SED of the galaxy from the literature (see Fig. 1 of KF97a); based on photon counting arguments, we found evidence for an optical coronal lines region dominated by OVIII absorption and high ionization parameters of NGC 4051 (Komossa & Fink 1997a) with their recent results, we find both to be consistent: For warm absorbers the question emerges whether this ionized material; in particular, the Fe lines [FeVII] λ6087, [FeX] λ6374, [FeXI] λ7892, and [FeXIV] λ5303 (see Tab. 2). We find that all of them are much weaker than observed!

We then varied those parameters that not strongly influence the X-ray absorption structure, but could have an effect on the predicted Fe line strengths; namely: the metal abundances, the gas density, the EUV continuum shape, the IR continuum strength. We find that in all cases, the lines [FeVII]–[FeXI] remain much weaker than observed by several orders of magnitude. The reason for this is that the warm absorber is always too highly ionized, with a totally negligible amount of Fe$^{+3}$ and Fe$^{+10}$ ions in the gas. Therefore, changes in collisional strengths for the relevant Fe transitions, which are still poorly known, are not expected to alter this result. We conclude that, for the case of NGC 4051, warm absorber and coronal line region are not one and the same component, but of different origin. This is consistent with the recent findings of Nagao et al. (2000) that the [FeXI] emission of NGC 4051 is not confined to the nucleus, but widely extended (out to at least ∼150 pc).

4.4. Comparison with subsequent studies

Recently Porquet et al. (1999; P99 hereafter) presented a parameter space study of the strengths of Fe coronal lines that originate from warm absorbers. They conclude that Fe lines in low-density absorbers (they studied the density range log $n_\text{H}$ = 8–12) are over-predicted for part of the parameter space. Comparing our earlier results on NGC 4051 (Komossa & Fink 1997a) with their recent results, we find both to be consistent: For warm absorbers dominated by OVIII absorption and high ionization parameters, no overprediction in line emission occurs (their Tab. 1).

The question remains whether the ‘OVII absorbers’ of P99 do indeed overpredict the Fe lines and thus are in conflict with observations. We suggest that most of the strong OVII absorbers likely contain dust (which was not included in the models of P99), as proposed by Reynolds (1997). The strong depletion of Fe into dust grains then results in weaker gas phase emission in the Fe coronal lines.

ability arguments we derive a limit on the density of the warm absorber, $n_\text{H} \lesssim 3 \times 10^7$ cm$^{-3}$, which translates into a distance from the nucleus of $\sim 3 \times 10^{16}$ cm.
Table 2. Predicted iron lines (Komossa & Fink 1997a) compared to the observed ones of NGC 4051 assuming a covering factor of the warm absorber of 50%; all lines are given relative to the observed Hβ luminosity of NGC 4051. Some notes: (i) The strongest predicted among the Fe lines in most models is Fe 19 λ1118; (ii) model results are robust against the small uncertainties in the reddening correction (e.g., we assumed $A_V = 0.7$mag, Nagao et al. (2000) used $A_V = 1$mag); (iii) all non-‘standard’ model sequences were first re-fit to the data, to derive the new best-fit WA parameters (which sometimes slightly differed from the old ones) before the lines were predicted [if this is not done, the predicted Fe lines change more strongly!] (iv) recent NLR (and torus-) related multi-component photoionization models of Sy 1s can successfully account for [FeVII] (e.g., Komossa & Schulz 1997, Murayama & Taniguchi 1998a,b).

| model             | line predictions | $[^{[}{FeVII}]/{[^{[}{FeX}]},[^{[}{FeXI}]}/[^{[}{Hβ_{obs}}]$ | $[^{[}{Fe XIV}]}/[^{[}{Hβ_{obs}}]$ | comments                                                                 |
|-------------------|------------------|-------------------------------------------------|-------------------------------|-------------------------------------------------------------------------|
| ‘standard’        | $< 5 \times 10^{-5}$, $< \text{obs.}$ | 0.004                                           | 0.3 $\leq Z \leq 1$          | observed: $F_{14}/Hβ < 0.06$ (Nagao et al. 2000)                         |
| var. abundances   | $''$             | change $\leq$ fact. 2-4                         | $4 \leq \log n_H \leq 9.5$  |                                                                         |
| var. density      | $''$             | $''$                                            | additional soft excess to account for $L_{Hβ}$ |
| var. IR conti.    | $''$             | $''$                                            | $log T_{vb} = 5, Q_{vb} = 4$  |
| var. EUV conti.   | $''$             | $''$                                            | up to the observed IR data points (from host galaxy) $\rightarrow$ increased f-f heating |
| ‘91 McHardy data  | $''$             | 0.02                                            | log $U = 0.2$, log $N_e = 22.47$ (our re-fit of the data originally presented by McHardy et al. 1995) |

4.5. A warm absorber relation to any optical/UV emission line component?

Finally, we note that our more general search for a warm-absorber origin of of one of the emission-line regions observed in the UV/optical spectra of Seyfert galaxies did not give a single example with a one-to-one match (see Komossa & Fink 1997e for a brief overview); emission lines from warm absorbers are always weaker than observed lines. However, the possibility of a (weak) warm-absorber contribution to individual emission lines (e.g., CIV in the case of NGC 3227; Komossa & Fink 1997b) remains.

5. The warm absorber of MR 2251–178

5.1. Introduction

MR 2251-178 at redshift $z=0.068$ was the first quasar to be discovered in X-rays, in the course of the Ariel V all-sky survey (Cooke et al. 1978, Ricker et al. 1978). It turned out to be an outstanding object in many respects. It has a high ratio of $L_x/L_{opt}$, is surrounded by a giant HII envelope observed in [OIII] emission, and was the first object in which a warm absorber was discovered (Halpern 1984). Based on EXOSAT and Ginga observations Pan et al. (1990) and Mineo & Stewart (1993), again, interpreted and modeled the data in terms of the presence of a warm absorber. In contrast, Walter & Courvoisier (1992), in an independent analysis explained the observations in terms of a variable powerlaw spectral shape, and concluded the presence of a warm absorber was unnecessary to explain the X-ray data. Reynolds (1997), in the course of a large sample study of ASCA observations of AGN reported the detection of OVII and OVIII absorption edges in the X-ray spectrum of MR 2251.

Here, we present first results from a detailed analysis of a deep archival ROSAT PSPC (Trümper 1983, Briel et al. 1994) observation of this source performed in Nov. 1993 with a duration of 18 ksec.

5.2. X-ray analysis: results

X-ray data reduction was carried out in a standard manner (see Komossa 2000, in prep.). In total, 36 X-ray sources were detected with a likelihood $\geq 10$ within the field of view. The positions of those in the vicinity of MR 2251 are shown in Fig. 3, overlaid on an optical image from the digitized Palomar sky survey.

The mean source countrate was 3.1 cts/s, a factor of 3 stronger than during the ROSAT all-sky survey observation performed in 1990. The X-ray lightcurve is displayed in Fig. 1.

First, we fit a single powerlaw to the total X-ray spectrum. Cold absorption was fixed to the Galactic value towards MR 2251, $N_{Gal} = 2.77 \times 10^{20}$ cm$^{-2}$ (Lockman & Savage 1995), since it is underpredicted otherwise. This gives $\Gamma_x = -2.3$ and clearly is a very poor description of the data ($\chi^2_{\text{red}} = 5.4$; Fig. 4). A Raymond-Smith emission model does not fit the spectrum at all, even if temperature, normalization, metal abundances and the amount of cold absorption are all treated as free parameters. We then tried two-component spectral fits involving a power-
law plus soft excess parametrized by different models. The quality of the fit remains unacceptable, though.

The presence of a warm absorber markedly improves the fit. Performing a two-edges fit with edge energies fixed at the theoretical values of OVII and OVIII we obtain $\tau_{\text{OVII}} = 0.26 \pm 0.12$, $\tau_{\text{OVIII}} = 0.20 \pm 0.12$, and $\Gamma_x = -2.20 \pm 0.02$. The not yet totally satisfactory quality of the fit, $\chi^2_{\text{red}} = 1.6$, can be traced back to a deviation of the low energy part of the spectrum (between 0.1–0.18 keV) from the model prediction which already caused an underprediction of the galactic $N_H$ in the pure powerlaw fit. If this part of the spectrum is excluded from the spectral fitting, we obtain $\chi^2_{\text{red}} = 0.9$, $\tau_{\text{OVII}} = 0.22 \pm 0.11$, $\tau_{\text{OVIII}} = 0.24 \pm 0.12$, and $\Gamma_x = -2.21 \pm 0.02$. We conclude that a warm absorber is clearly present in this source.

6. The X-ray transient AGN RXJ0134-4258

6.1. Summary of the observations

The Narrow-line Seyfert 1 galaxy RXJ0134-4258 is one of the rare sources which showed dramatic spectral variability. Its spectrum changed from ultrasoft ($\Gamma_x = -4.3$) in the ROSAT all-sky survey (RASS) to flat ($\Gamma_x = -2.2$) in our pointed PSPC observation taken two years later while its countrate remained nearly constant (Greiner 1996, Komossa & Fink 1997d, Komossa & Greiner 1999, Komossa et al. 1999b, Grupe et al. 2000, Komossa & Meerschweinchen 2000).

One possible explanation for this kind of spectral variability is the presence of a warm absorber. In particular, we have studied the following two scenarios (details are given in Komossa & Meerschweinchen 2000; KM2000 hereafter):

6.2. Explanations invoking a warm absorber

Changes in ionization state of a warm absorber: We find that a warm absorber of ionization parameter $\log U \simeq 0.5$ and column density $\log N_{H} \simeq 23$ fits well the RASS observation of this source ($\chi^2_{\text{red}} = 0.6$; Fig. 8). To account then for the much flatter spectrum during the later PSPC observation requires a change in ionization state of the warm absorber. Since the intrinsic luminosity of the source did not vary strongly from one to the other observation, it is then required that the ionization state of the warm absorber reflects the (unobserved) history of the variability in the intrinsic luminosity (see KM2000 for details). After allowing for non-equilibrium effects in the absorber and/or a range in densities, such a warm absorber is consistent with the long- and short-timescale variability behavior of RXJ0134-4258. We did not favor this possibility in our earlier work, because it introduces a new level of complexity (more free parameters) as compared to the simpler case of an absorber in equilibrium.

Cloud passing our line-of-sight: Alternatively, a cloud of ionized material may have passed our line of sight during the RASS observation, and has (nearly) disappeared during the later PSPC observation (see KM2000 for details).

In summary, we find that a warm absorber fits well the ROSAT survey observation, and residuals around the expected location of absorption edges are still present during our later pointed PSPC observation. In addition, the presence of high-ionization UV absorption lines in this object was recently reported by Goodrich (talk at the Narrow-line Seyfert 1 workshop in Bad Honnef, Dec. 1999), and the recent study by Crenshaw et al. (1999) suggests a near one-to-one match of the presence of UV and X-ray warm absorbers.

We conclude, that the presence of a time-variable warm absorber is a viable explanation for all available X-ray observations of RXJ0134-4258. High-spectral resolution data taken during episodes of repeated spectral variability of this source are required to distinguish this from other possible scenarios like real changes in the steepness of the powerlaw or a powerlaw plus soft excess description (see Komossa & Meerschweinchen 2000).

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Preprints of this and related papers can be retrieved from our webpage at http://www.xray.mpe.mpg.de/~skomossa/

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7 The flat-state spectrum shows two kinds of residuals when fit by a single powerlaw (cf Fig. 9): Deviations of the lowest energy bins near 0.1 keV suggesting the presence of a very soft excess (or instrumental features; they are similar to the ones seen in MR 2251, Sect. 5.2), and deviations near the expected locations of the WA absorption edges. No single-component fit can remove all residuals. The simultaneous presence of both, a soft excess and a warm absorber is well possible, but such fits would be an over-representation of the PSPC spectral resolution. Since both features, very soft excess and warm absorber (note the redshift of RXJ1242) are outside or very close to the border of the ASCA sensitivity range, further observations with the new generation X-ray telescopes are required to search for these features.
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Fig. 3. Intrinsic warm absorber emission in CIVλ1549/Hβ_{WA}, in dependence of ionization parameter $U$ for different densities and X-ray continuum shapes ($\alpha_{EUV}$ was fixed to -1.4). Solid line: spectrum with $\Gamma_x = -1.9$, log $N_w = 21.5$ und log $n_H = 9.5$; dashed: $\Gamma_x = -1.6$; dotted: $\Gamma_x = -1.9$, log $n_H = 7.0$ and, increasing from left to right) log $N_w = 21.35, 21.5, 21.65$.

Fig. 4. Emission line spectra in the range 600 – 2900 Å predicted to arise from a warm absorber with $U = 0.1$ and log $N_w = 21.5$ (bottom) compared to the mean BLR spectrum (top; Netzer 1990). The y-axis gives the intensity ratio relative to Hβ. In the bottom panel, the absorber-intrinsic emission lines were scaled to the mean observed Hβ luminosity of NGC 3227, to give an impression on the strengths of these lines and allow a judgement of their detectability.

Fig. 5. X-ray sources detected in a 10′ × 10′ field around MR 2251-178 superimposed on an optical image. The circles drawn around the X-ray source positions are of 20″ radius.
Fig. 6. X-ray lightcurve of MR 2251-178, binned to time intervals of 400 s. The time is measured in seconds from the start of the pointed observation. The mean countrate during the RASS, not shown, was 1 cts/s.

Fig. 7. The upper panel shows the observed X-ray spectrum of MR 2251 (binned to S/N=35; crosses) and the best-fit powerlaw model (solid line). The second panel displays the fit residuals for this model, whereas the lowest panel gives the residuals from a warm absorber fit parameterized by two absorption edges (note the different scale of the ordinate). The lowest energy bins were ignored in this fit (see text for details).

Fig. 8. Residuals after fitting a warm absorber to the RASS spectrum (= ‘steep-state’ spectrum) of RXJ0134-4258.

Fig. 9. Residuals after fitting a powerlaw to the pointed PSPC data (= ‘flat-state’ spectrum) of RXJ0134-4258 (see also footnote 7).