

The complex X-ray spectra of active galaxies with warm absorbers

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ABSTRACT

Warm absorbers are an important new probe of the central regions of active galaxies (AGN). So far, they revealed their existence mainly in the soft X-ray spectral region. In observing and modeling this component, we can learn a lot 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.

Here, we briefly review the basic X-ray spectral features of warm absorbers (dust-free WAs, dusty WAs, peculiar ~ 1.1 keV absorption, emission and reflection components) and then discuss these in more detail based on analyses of individual objects observed with the X-ray satellite *ROSAT*. The importance of *XMM* in improving our knowledge of the warm material is discussed.

1. Introduction

Warm absorbers reveal their presence by imprinting absorption edges on the soft X-ray spectra of active galaxies (cf. Fig. 1). These provide an important diagnostic of the AGN central region. The presence of an ionized absorber was first discovered in *Einstein* observations of the quasar MR 2251-178 (Halpern 1984). With the availability of higher-quality soft X-ray spectra from *ROSAT* and *ASCA*, several more warm absorbers were found: they are seen in about 50% of the well studied Seyfert galaxies (e.g., Nandra et al. 1993, Turner et al. 1993, Weaver et al. 1994, Cappi et al. 1996, Mathur et al. 1997, Komossa et al. 1997c) as well as in some quasars (e.g. Fiore et al. 1993, Ulrich-Demoulin & Molendi 1996, Schartel et al. 1997). More than one warm absorber imprints its presence on the soft X-ray spectrum of MCG-6-30-15 (e.g., Otani et al. 1996) and NGC 3516 (Kriss et al. 1996). Particularly in these latter cases, improved X-ray spectral resolution is required to clearly separate both components.

Besides the absorption edges, the ionized absorber modifies the soft X-ray spectrum by emission lines, as emphasized by Netzer (1993). These lines contain important additional information about the physical conditions of the ionized material. Whereas the detection of such lines was reported for NGC 3783 (George et al. 1995), their contribution (as calculated with the code *Cloudy*) was found to be negligible for the best-fit warm absorbers in NGC 4051 and NGC 3227 (Komossa & Fink 1997a,b). Emission features of the warm material are best detectable against the reflected continuum component, i.e. if the direct component is completely absorbed (cf. Fig. 1).

In the last two years, evidence has accumulated that some warm absorbers contain significant amounts of dust. This possibility was suggested by Brandt et al. (1996) to explain the lack of excess X-ray *cold* absorption despite strong optical reddening of the quasar IRAS 13349+2438. Explicit photoionization modelling of dusty warm gas using the code *Cloudy* showed that the modifications of the X-ray absorption spectrum can be quite strong in the presence of dust, particularly for high column densities of the warm absorber (Komossa & Fink 1997a-d, Komossa & Bade 1998).

Another interesting recent development is the detection of spectral complexity around 1.1 keV (e.g., Hayashida 1997). ‘Standard’ warm absorber models do not predict strong absorption features around this energy; usually, the deepest edges are those of oxygen OVII and OVIII at 0.74 and 0.87 keV, respectively. Among the suggested interpretations for the 1.1 keV feature is strongly blueshifted oxygen absorption, implying relativistic outflow velocities (e.g., Leighly et al. 1997a).

In the following, we first discuss two suggested candidates for dusty warm absorbers, IRAS 13349+2438 and 4C+74.26, and predict the characteristic absorption features observable with *XMM*. We then investigate several scenarios to explain the peculiar spectral features around 1.1 keV. The analyses are based on *ROSAT* X-ray observations and photoionization calculations carried out with the code *Cloudy* (Ferland 1993).

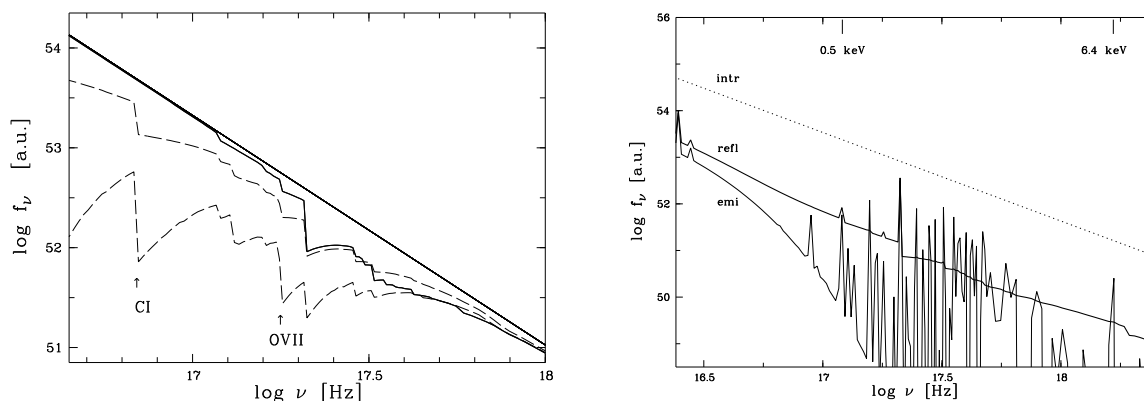


Fig. 1.— **Left:** Changes of the X-ray absorption spectrum in the presence of dust. The thin straight line represents the intrinsic continuum, the fat line shows a dust-free warm absorber. The dashed lines correspond to the same model after inclusion of dust and depleted gas-phase metal abundances. The dust was depleted relative to the standard Galactic-ISM mixture by factors of 10 (upper dashed curve) and 3 (lower dashed curve). A characteristic feature of (the graphite species of) dust is the strong edge of neutral carbon, labeled CI. **Right:** Spectral components of warm material seen in emission and reflection, calculated with Ferland’s code *Cloudy* (see Komossa et al. 1998). The incident continuum is shown as dotted line. The thin solid line corresponds to the emitted spectrum and the thick solid line to the reflected spectrum. The abscissa brackets the energy range 0.1 – 10 keV.

2. Dusty warm absorbers

2.1. IRAS 13349+2438

This quasar received a lot of attention, recently. In X-rays, the presence of a dusty warm absorber was suggested (Brandt et al. 1996). Here, we fit a model that explicitly includes the presence of dust to the *ROSAT* X-ray spectrum. Although repeatedly suggested, such a model has not been applied previously (for some results see Komossa & Fink 1998). Given the potentially strong modifications of the X-ray absorption spectrum in the presence of dust, it is important to scrutinize whether a dusty warm absorber is consistent with the observed X-ray spectrum. Since some strong features of dusty warm absorbers appear outside the *ASCA* sensitivity range, *ROSAT* data are best suited for this purpose; we used the pointed PSPC observation of Dec. 1992.

In a first step, we fit a *dust-free* warm absorber (as in Brandt et al. 1996, but using the additional information on the hard X-ray powerlaw available from the *ASCA* observation, $\Gamma_x^{2-10\text{keV}} \simeq -2.2$; Brinkmann et al. 1996, Brandt et al. 1997). This gives an excellent fit with $\log N_w = 22.7$ ($\chi_{\text{red}}^2 = 0.84$). If this same model is re-calculated by fixing N_w and the other best-fit parameters but *adding dust* to the warm absorber the X-ray spectral shape is drastically altered and the data can not be fit at all ($\chi_{\text{red}}^2 = 150$). This still holds if we allow for non-standard dust, i.e., selectively exclude either the graphite or silicate species. It has to be kept in mind, though, that the expected column derived from optical extinction is less than the X-ray value of N_w determined under the above assumptions. Therefore, in a next step, we allowed all parameters (except Γ_x) to be free and checked, whether a dusty warm absorber could be successfully fit at all. This is not the case (e.g., if N_w is fixed to $\log N_{\text{opt}} = 21.2$ we get $\chi_{\text{red}}^2 = 40$). The bad fit results can be partially traced back to the ‘flattening’ effect of dust. In fact, if we allow for a steeper intrinsic powerlaw spectrum, with $\Gamma_x \simeq -2.9$ much steeper than the *ASCA* value, a dusty warm absorber with $N_w = N_{\text{opt}}$ fits the *ROSAT* spectrum well ($\chi_{\text{red}}^2 = 1.2$). We also analyzed the *ROSAT* survey data and find the same trends. At present, there are several possible explanations for the *ROSAT-ASCA* spectral differences: (i) variability in a *two*-component warm absorber, (ii) variability in the intrinsic spectrum, or (iii) remaining *ROSAT-ASCA* cross-calibration uncertainties.

2.2. 4C+74.26

In an analysis of *ROSAT* and *ASCA* data of the radio-loud quasar 4C+74, Brinkmann et al. (1998) find an unusually flat soft X-ray *ROSAT* spectrum ($\Gamma_x \simeq -1.3$ to -1.6 ; as compared to $\Gamma_x \simeq -2.2$ typically seen in radio-loud quasars), a steeper *ASCA* powerlaw (PL) spectrum, and evidence for the presence of a warm absorber. Applying the model of a *dusty* warm absorber to the *ROSAT* spectrum we get a successful spectral fit, with a steeper intrinsic PL spectrum (now consistent with the *ASCA* value and the general expectation for radio-loud quasars), and a

column density N_w consistent with optical reddening. However, excess cold absorption provides an alternative successful spectral fit, and higher X-ray spectral resolution is required to exclude a cold absorber.

2.3. The role of XMM

Besides IRAS13349, several more good candidates for dusty warm absorbers have been presented (NGC 3227, Komossa & Fink 1997b; NGC 3786, Komossa & Fink 1997c; MCG-6-30-15, Reynolds et al. 1997; IRAS17020+4544, Leighly et al. 1997b, Komossa & Bade 1998) which suggests this component to be common in all types of AGN. Signatures of the presence of dust are a carbon edge at 0.28 keV and an oxygen edge at 0.56 keV, produced by inner-shell photoionization, not yet individually resolved by current X-ray instruments. Therefore, one main argument in favour of dust within the warm absorber remained an indirect one: the discrepancy between the *large* amount of cold absorbing material inferred from optical data, and the *small or negligible* excess cold absorption derived from the X-ray spectral analysis. The detection of the predicted absorption features with XMM will therefore be an important and necessary confirmation of the existence of *dusty* warm absorbers. It will then provide an interesting new approach to study the properties of dust in other galaxies, since the individual metal absorption edges reflect the dust composition and amount of dust.¹

3. Peculiar 1.1 KeV absorption: PG 1404+226

The *ROSAT* high-state and *ASCA* spectrum of the luminous Sy galaxy PG 1404 show evidence for unexpectedly strong 1.1 keV absorption (Ulrich & Molendi 1996, Comastri et al. 1997, Leighly et al. 1997a). Here, on the basis of detailed photoionization modelling of the absorbing material under various conditions, we explore several scenarios to account for the 1.1 keV absorption *without* invoking relativistic outflow:

- a ‘standard’ warm absorber of high ionization parameter, including a strong contribution from emission and reflection;
- non-solar abundances (over-abundant neon or under-abundant oxygen);
- an additional soft excess overlapping with the absorption features (soft excess added to the *incident* continuum that illuminates the warm absorber).

The following results are obtained: **(i)** Models of high ionization parameter U and/or with the emission and reflection component added to the observed spectrum were calculated for a

¹Note that in case the dust is mixed with *cold* gas, X-ray dust features would be extremely difficult to detect, since they are hard to distinguish from gas-phase absorption due to the same element; the shift of the edge energy due to solid state effects is only of the order of a few eV (e.g., Greaves et al. 1984).

covering factor of 0.5. In application to PG 1404, fitting such a model improves the quality of the fit, but the high-state data are still not well matched. **(ii)** One way to clearly change the depth of individual absorption edges, and particularly to make the neon absorption dominate over oxygen in strength, is a deviation from solar abundances, of either overabundant neon or underabundant oxygen. Several deviation factors were studied between an abundance of up to $O = 0.2 \times$ solar and up to $Ne = 4 \times$ solar. These models strongly improve the quality of the fit to PG 1404 up to acceptable values (cf. Tab. 2 of Komossa & Fink 1998). A potential problem for this model description, besides a difficulty to explain strong deviations of O/Ne from the solar value in terms of nucleosynthesis, is the location of the deepest edge. In order to weaken sufficiently the oxygen absorption, a rather high ionization parameter is required with the consequence that the deepest neon edges are those of highly ionized species, around 1.36 keV, instead of 1.1 keV. **(iii)** Motivated by the *ASCA* evidence for soft excesses in some NLSy1s, a sequence of models was calculated with an additional hot black body component of $T = 0.1$ keV. This component was included in the ionizing SED that irradiates the absorber, i.e. the change in ionization structure of the warm material was self-consistently calculated. This causes a complex spectral shape in the 1 keV region, with the down-turning soft-excess and some Ne-K and Fe-L absorption contributing to the X-ray features which then sensitively depend on the strength of the soft excess (cf. Fig. 2 of Komossa & Fink 1998). (Note that the black body spectrum is *incident* on the warm material, and not added afterwards as separate component; this causes a different ionization structure and therefore soft X-ray spectral shape.) A successful description of both, high- and low-state *ROSAT* data is possible, but a rather broad edge structure is predicted. Data of high spectral resolution will be needed to discriminate between these models, the interesting alternatives of relativistic outflow or high iron overabundance, or further scenarios to account for the 1.1 keV features.

4. Summarizing conclusions

Warm absorbers display many facets and may account for a variety of observational phenomena, mostly in the X-ray spectral region. Their detailed study will certainly be a prime goal of the X-ray satellite *XMM*. In particular, *dust*-created absorption edges, if confirmed, 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 new diagnostic of dust properties in other galaxies.

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