Properties of warm absorbers in active galaxies

Stefanie Komossa and Henner Fink†
Max–Planck–Institut für extraterrestrische Physik, Giessenbachstraße, 85740 Garching, Germany

Abstract. We present a study of the nature of warm absorbers on the basis of ROSAT X-ray observations and photoionization calculations carried out with the code Cloudy. We focus on ‘non-standard’ warm absorbers: (i) the proposed dusty warm absorbers in IRAS 13349+2438 and IRAS 17020+4544, and possibly in 4C +74.26, (ii) we explore several scenarios to account for the recently observed peculiar absorption features around ∼1.1 keV on the basis of detailed photoionization models, and apply these to PG 1404+226.

1. Introduction

Absorption edges in the X-ray spectra of Seyfert galaxies have been interpreted as the signature of ionized gas along the line of sight to the active nucleus. These so-called ‘warm absorbers’ provide an important new diagnostic of the AGN central region. So far, they revealed their existence mainly in the soft X-ray spectral region. The physical state and location of the ionized material and its relation to other components of the active nucleus is still rather unclear. E.g., an outflowing accretion disk wind and various BLR related models have been suggested.

We performed a study of the properties of warm absorbers based on ROSAT (Trümper 1983) X-ray observations and photoionization calculations carried out with the code Cloudy (Ferland 1993). Results on the warm absorbers in NGC 4051, NGC 3227, NGC 3786, Mrk 1298 were presented earlier in Komossa & Fink (1997a-d, respectively). Here, we focus on ‘non-standard’ warm absorbers: (i) we comment on the influence of dust on the X-ray absorption structure

(Fig. 1). Changes of the X-ray absorption spectrum in the presence of dust. The thin straight line marks 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.

2. Warm absorbers with internal dust

2.1. Influence of dust on the X-ray absorption structure

Recently, evidence has accumulated that some warm absorbers contain significant amounts of dust. This possibility was first suggested by Brandt et al. (1996) to explain the lack of excess X-ray cold absorption despite strong optical reddening (hereafter referred to as ‘N_{opt} − N_{x} discrepancy’) of the quasar IRAS 13349+2438.

As we emphasized earlier (Komossa & Fink, e.g. 1997a,b; Komossa & Bade 1998) and demonstrate here in Fig. the influence of the presence of dust on the X-ray absorption spectrum can be strong, and becomes drastic for high column densities N_{g}. Signatures of the presence of (Galactic-ISM-like) dust are, e.g., a strong carbon edge.
in the X-ray spectrum, and a stronger temperature gradient across the absorber with more gas in a ‘colder’ state. Another interesting property is the increased sensitivity of dusty gas to radiation pressure, which may drive strong outflows of the warm material.

### 2.2. 4C+74.26

4C+74 is a radio-loud quasar. In an analysis of ROSAT and ASCA data, 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 (Tab. 1). Alternatively, excess cold absorption of large column density fits the ROSAT spectrum, and better spectral resolution soft X-ray data are needed to exclude a cold absorber.

### 2.3. IRAS 17020+4544

A dusty warm absorber was suggested to be present in the NLSy1 galaxy IRAS 17020 (Leighly et al. 1997b) on the basis of an $N_{\text{opt}} - N_e$ discrepancy and the presence of an absorption edge in the ASCA spectrum.

When fit by a single powerlaw, the ROSAT X-ray spectrum of IRAS 17020 is rather steep ($\Gamma_x = -2.4$). Checking whether (and under which conditions) a dusty warm absorber fits the ROSAT X-ray spectrum, we find that an even steeper intrinsic spectrum is required to compensate for the ‘flattening effect’ (cf. Fig. 1) of dust (Tab. 1); for details on IRAS 17020 see Komossa & Bade (1998).

The presence of a dusty warm absorber in IRAS 17020 particularly adds to the spectral complexity in NLSy1 galaxies. Whereas early NLSy1 models tried to explain their very steep observed X-ray spectra by only one component (either a strong soft excess, or a warm absorber, or an intrinsically steep spectrum), there is now evidence that often all three components are simultaneously present, and the additional presence of dusty material partly compensates the ‘steepening effect’ of the other three.

### 2.4. IRAS 13349+2438

This quasar received a lot of attention, recently. A detailed optical study was presented by Wills et al. (1992). In X-rays, the presence of a dusty warm absorber was suggested (Brandt et al. 1996). Brinkmann et al. (1996) detected changes in the ASCA spectrum as compared to the earlier ROSAT data; the warm-absorption features remained present (Brandt et al. 1997). Here, we apply the model of a dusty warm absorber to the ROSAT X-ray spectrum. Although repeatedly suggested, such a model has not been fit previously (for first results see Komossa 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 two pointed PSPC observations of Jan. 1992 and Dec. 1992 (P-2 hereafter).

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, $\Gamma_x = -2.2$). This gives an excellent fit with log $N_w = 22.7$ ($\chi^2_{\text{red}} = 0.84$ for P-2). 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 ($\chi^2_{\text{red}} = 150$). 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.

### Table 1. Properties of the warm absorbers from X-ray spectral fits and results from a single powerlaw fit for comparison.

|          | dusty warm absorber | single powerlaw |
|----------|---------------------|-----------------|
|          | $\Gamma_x$ | log $U$ | log $N_w$ | $\chi^2_{\text{red}}$ | $\Gamma_x$ | $\chi^2_{\text{red}}$ |
| 4C+74.26 | -2.2 | -0.1 | 21.6 | 1.0 | -1.4 | 1.0 |
| IRAS 17020+4544 | -2.8 | 0.7 | 21.6 | 0.8 | -2.4 | 0.8 |
| sil(2)   | -2.4 | 1.0 | 21.6 | 0.9 |          |      |
| IRAS 13349+2438 | -2.9 | -0.4 | 21.2 | 1.2 | -2.8 | 1.3 |
| df(3)    | -2.2 | 0.7 | 22.7 | 0.8 |          |      |

(1) fixed to the value $N_{\text{opt}}$ determined from optical reddening; (2) silicate species of dust only; (3) dust-free warm absorber for comparison.
Therefore, in a next step, we allowed all parameters (except $\Gamma_x$) 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 $\chi^2_{\text{red}} = 40$).

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 ($\chi^2_{\text{red}} = 1.2$, Tab. 1). 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 powerlaw, or (iii) remaining ROSAT-ASCA inter-calibration uncertainties.

3. Peculiar 1.1 KeV absorption

Recently, several cases of spectral complexity around 1.1 keV have been reported (e.g., Hayashida 1997). Among these is PG 1404+226. Its ROSAT high-state and ASCA spectrum show evidence for unexpectedly strong 1.1 keV absorption (Ulrich & Molendi 1996, Comastri et al. 1997). If interpreted in terms of blueshifted oxygen, exceptionally high outflow velocities are implied (e.g., Leighly et al. 1997a); an exciting possibility.

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 of the warm absorber (WA):

3.1. WA with contribution from emission and reflection

Models of high ionization parameter $U$ and/or with the emission and reflection component added to the observed spectrum, were calculated for a 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.

3.2. WA with non-solar O/Ne ratio

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 (Fig. 2), 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 (Tab. 2). 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 width of the X-ray absorption feature and the location of the deepest edge. Always, several ionization stages of neon coexist, leading to a broad absorption structure. Further, 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 (Fig. 2).
2). (Note that, since the bb is sensitively depend on the strength of the soft excess (Fig. 2), sorption contributing to the X-ray features which then 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 (Fig. 2). (Note that, since the bb 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 again a rather broad absorption feature is predicted (Fig. 2).

In the latter two cases (3.2 and 3.3) the difference between high-state and low-state spectrum could be explained by higher ionization parameter in high-state or variable strength of the soft excess. The results are summarized in Tab. 2.

Data of high spectral resolution will be needed to finally discriminate between these models, the interesting alternatives of relativistic outflow (Leighly et al. 1997a) or high iron overabundance (Comastri et al. 1997), and further scenarios to account for the 1.1 keV features.

### Table 2. X-ray spectral fits to the high-state (HS) and low-state (LS) ROSAT data of PG 1404. $\Gamma_x$ was fixed to $-1.9$. Errors in $U$, $N_w$ are about a factor 2–3.

| state     | log $U$ | log $N_w$  | $\chi^2_{\text{red}}$ | model                                      |
|-----------|---------|------------|------------------------|--------------------------------------------|
| HS/LS     | 4.1/2.0 |            |                        | single PL                                  |
| HS/LS     | 23.7/23.4 | 2.5/0.9    |                        | standard warm absorber                      |
| HS/LS     | 23.8/23.5 | 2.2/0.9    |                        | emission+reflection added                  |
| HS/LS     | 23.3/22.9 | 1.3/0.9    |                        | Ne = 4×solar abundance                     |
| HS/LS     | 23.1/23.1 | 1.2/1.0    |                        | additional 0.1 keV soft excess$^{(2)}$     |

(1) fixed to value derived for HS; (2) abundances reset to solar

### 3.3. Additional soft-excess incident on WA

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 illuminates 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 (Fig. 2). (Note that, since the bb 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 again a rather broad absorption feature is predicted (Fig. 2).

In the latter two cases (3.2 and 3.3) the difference between high-state and low-state spectrum could be explained by higher ionization parameter in high-state or variable strength of the soft excess. The results are summarized in Tab. 2.

Data of high spectral resolution will be needed to finally discriminate between these models, the interesting alternatives of relativistic outflow (Leighly et al. 1997a) or high iron overabundance (Comastri et al. 1997), and further scenarios to account for the 1.1 keV features.

### 4. Summarizing conclusions

There is good evidence that several warm absorbers contain dust as signified by multi-\(\lambda\) evidence and successful X-ray spectral fits. The influence of dust on the X-ray absorption structure can be strong. Dusty warm absorbers are found to be consistent with the X-ray spectra of 4C 74, IRAS 17020, and IRAS 13349. Whereas in the first case, the flattening effect of dust leads to consistency of the intrinsic X-ray spectrum with the ASCA shape and general expectations, in the latter case a rather steep ROSAT spectrum is required.

These several good cases of dusty warm absorbers suggest this component to be common in all types of AGN. Clear signatures of the presence of dust are a carbon edge at 0.28 keV and an oxygen edge at 0.56 keV, not yet individually resolved by current X-ray instruments. The study of these features with future missions will provide an interesting approach to investigate dust properties in other galaxies. But not all warm absorbers contain dust (cf. Komossa & Fink 1997a, Komossa 1998).

Several scenarios to explain the recently observed unusual 1.1 keV absorption feature were studied. Among these, non-solar O/Ne-ratio and the presence of an additional soft excess illuminating the warm gas are found to fit the ROSAT X-ray spectrum of PG 1404. Potential problems of these and alternative model descriptions are pointed out.

In summary, warm absorbers display many facets and may account for a variety of observational phenomena. Their detailed study will certainly be an important goal of future X-ray satellites like AXAF and XMM.

### Acknowledgements

I gratefully remember Henner Fink for introducing me to the work with X-ray data, for many discussions and helpful advice. Henner Fink passed away in December 1996. It is a pleasure to thank Marie-Helene Ulrich and Andrea Comastri for stimulating discussions on PG 1404, Gary Ferland for providing Cloudy, and Emmi Meyer-Hofmeister for her continuing kind interest.

### References

Brandt W.N. et al., 1996, MNRAS 278, 326; 1997, MNRAS 292, 407

Brinkmann W. et al., 1996, A&A 316, L9; 1998, A&A 330, 67

Comastri A. et al., 1997, in X-Ray Imaging and Spectr. of Cosm. Hot Plasmas, F. Makino, K. Mitsuda (eds), 279

Ferland G.J., 1993, University of Kentucky, Physics Department, Internal Report

Hayashida K., 1997, in Emission Lines in AGN, B.M. Peterson et al. (eds), ASP conf. ser. 113, 40

Komossa S., 1998, in Structure and Kinematics of Quasar Broad Line Regions, M. Gaskell et al. (eds), ASP conf. ser., in press

Komossa S., Fink H., 1997a, A&A 322, 719; 1997b, A&A 327, 483; 1997c, A&A 327, 555

Komossa S., Fink H., 1997d, in Accretion Disks – New Aspects, E. Meyer-Hofmeister, H. Spruit (eds), Lecture Notes in Physics 487, 250
Komossa S., Bade N., 1998, A&A 331, L49
Leighly K., et al., 1997a, ApJ 489, L25; 1997b, ApJ 489, L137
Trümper J., 1983, Adv. Space Res. 2, 241
Ulrich-Demoulin M.-H., Molendi S., 1996, ApJ 457, 77
Wills B.J. et al., 1992, ApJ 400, 96