Warm absorbers in Narrow-Line Seyfert 1 galaxies

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Abstract. Warm absorbers are an important new tool for investigating the 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 (NLSy1). Here, we present a study of the X-ray properties of several NLSy1s with focus on their warm absorbers: (a) An analysis of all *ROSAT* PSPC observations of NGC 4051 including new ones is performed, which reveals variability by a factor ~30 in count rate and much less variability in the warm absorber parameters. (b) The possibility of a *dusty* warm absorber in IRAS 13349+2438 is explored on the basis of photoionization models for dusty warm gas and explicit *ROSAT* spectral fits. (c) The X-ray spectrum of the NLSy1 1E 0117.2-2837 is analyzed. It can be successfully described by a very steep powerlaw of photon index $\Gamma_x \simeq -4$, or alternatively by a warm-absorbed flat powerlaw. UV-EUV emission lines expected to arise from the warm material are predicted. (d) The strong spectral variability of RX J0134.3-4258 (from $\Gamma_x \simeq -4.4$ in the *ROSAT* survey observation, to $\simeq -2.2$ in our subsequent pointing) is examined in terms of warm absorption.

1. Introduction

The presence of an ionized absorber was first discovered in *Einstein* observations of the quasar MR 2251-178 (Halpern 1984). With the improved spectral resolution of *ROSAT* and *ASCA*, many more were found. So far, they revealed their existence mainly in the soft X-ray spectral region, via absorption edges of highly ionized metal ions. Their physical state, location and relation to other components of the active nucleus is still rather unclear. E.g., an accretion disk wind and various BLR related models have been suggested. Warm absorbers have been observed in ~50% of the well-studied Seyfert galaxies and some quasars. Characteristic X-ray absorption edges also show up in quite a number of NLSy1 galaxies (e.g., Leighly et al. 1996, Wang et al. 1996, Guainazzi et al. 1996, Brandt et al. 1997, Komossa & Fink 1997a, Hayashida 1997, Iwasawa et al. 1998) and we focus on this sub-group in the present contribution. We use the definition of NLSy1 'loosely', i.e., we include the quasar IRAS 13349+2438 which shares some similarities with NLSy1s (Brandt et al. 1996, B96 hereafter).

2. A *dusty* warm absorber: IRAS 13349+2438

Recently, evidence has accumulated that some warm absorbers contain significant amounts of dust (B96, Komossa & Fink 1996, Reynolds 1997, Komossa & Fink 1997b-d, Reynolds et al. 1997, Leighly et al. 1997, Komossa & Bade 1998, Komossa 1998). The possibility of a *dusty* warm absorber in IRAS 13349 was suggested by B96 to explain the lack of excess X-ray *cold* absorption despite strong optical reddening (for follow-up *ASCA* observations see Brinkmann et al. 1996, Brandt et al. 1997). As emphasized by Komossa & Fink (KoFi hereafter, e.g. 1997a,b) and Komossa & Bade (KoBa, 1998) the influence of the presence of dust on the X-ray absorption spectrum can be strong and becomes drastic for high column densities $N_{\rm w}$. 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 'cold' state.

Here, we apply the model of a *dusty* warm absorber to the *ROSAT* X-ray spectrum of IRAS 13349. Although repeatedly suggested, such a model has not been fit previously (for some 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 pointed PSPC observation of Dec. 1992. As ionizing continuum illuminating the warm absorber we adopted a mean Seyfert spectrum consisting of piecewise powerlaws (as in KoFi 1997b) with energy index $\alpha_{\rm EUV} = -1.4$. We use as definition for the ionization parameter $U = Q/(4\pi r^2 n_{\rm H} c)$. The photoionization calculations were carried out with Ferland's (1993) code *Cloudy*.

In a first step, we fit a dust-*free* warm absorber (as in B96, but using the additional information on the hard X-ray powerlaw available from the ASCA observation, $\Gamma_{\rm x}^{2-10{\rm keV}} \simeq -2.2$). This gives an excellent fit with log $N_{\rm w}$=22.7 ($\chi^2_{\rm red} = 0.8$). If this same model is re-calculated by fixing $N_{\rm w}$ 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 ($\chi^2_{\rm red} = 150$). 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 $N_{\rm w}$ determined under the above assumptions. Therefore, in a next step, we allowed all parameters (except $\Gamma_{\rm x}$) to be free and checked, whether a dusty warm absorber could be fit. This is not the case (e.g., if $N_{\rm w}$ is fixed to log $N_{\rm opt} = 21.2$ we get $\chi^2_{\rm red} = 40$).

The bad fit results can be partially traced back to the 'flattening' effect of dust (cf. Fig. 4 of KoBa 1998). In fact, if we allow for a steeper intrinsic powerlaw spectrum, with $\Gamma_{\rm x} \simeq -2.9$ much steeper than the *ASCA* value, a dusty warm absorber with $N_{\rm w} = N_{\rm opt}$, the value derived from optical reddening, fits the *ROSAT* spectrum well ($\chi^2_{\rm red} = 1.2$, Tab. 1). We also analyzed the *ROSAT* survey data and find the same trends; i.e., the requirement of a steep intrinsic *ROSAT* spectrum. 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.

The presence of a *dusty* warm absorber in the NLSy1-like quasar IRAS 13349 and the NLSy1 galaxy IRAS 17020+4544 (Leighly et al. 1997, KoBa 1998) further 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.

The detection of dust absorption features in the X-ray spectra of active galaxies with future X-ray missions will be an important check and confirmation of the existence of *dusty* warm absorbers, and will provide an interesting approach to investigate dust properties in other galaxies. But not all warm absorbers contain dust.

Table 1. X-ray warm absorber (WA) fits to IRAS 13349.

	warm absorber				single powerlaw	
	$\Gamma_{\rm x}$	log U	log $N_{\rm w}$	$\chi^2_{\rm red}$	$\Gamma_{\rm x}$	$\chi^2_{\rm red}$
dusty WA	–2.9	–0.4	$21.2^{(1)}$	1.2	–2.8	1.3
dust-free WA	–2.2	0.7	22.7	0.8		

$^{(1)}$ fixed to the value $N_{\rm opt}$ determined from optical reddening

3. Dust-free warm absorber: NGC 4051

The NLSy1 galaxy NGC 4051 harbours a warm absorber of high column density. In this case, only a dust-free warm absorber fits the X-ray spectrum. This can be traced back to the strong modifications of the absorption structure in the presence of dust.[1]

During a deep PSPC X-ray observation of Nov. 1993 the flux of NGC 4051 turned out to be strongly variable, the warm absorption features remained constant. This can be used to derive a constraint on the density and location of the ionized material, which yields $n \lesssim 3\,10^7 {\rm cm}^{-3}$ and $r \gtrsim 3\,10^{16}$ cm (see KoFi 1997a for details).

To investigate the long-term trend in the variability of NGC 4051, in count rate as well as in ionization parameter U and column density $N_{\rm w}$ of the warm absorber, we analyzed previously unpublished *ROSAT* PSPC observations of NGC 4051 and also re-analyzed data earlier presented in Mc Hardy et al. (1995). We find that in the long term all features are variable, except for the cold

[1] We find hints in the X-ray spectrum of NGC 4051 for a second, more lowly ionized warm absorber that may be dusty, but better-than-available spectral resolution is needed to check this.

absorption which is always consistent with the Galactic value within the error bars. U and $N_{\rm w}$ change by about a factor of 2. The slope of the powerlaw remains rather steep. We detect large-amplitude variability by a factor $\sim$30 in count rate within the total observing interval. The long-term X-ray lightcurve is shown in Fig. 1, the best-fit warm-absorber parameters are given in Tab. 2.

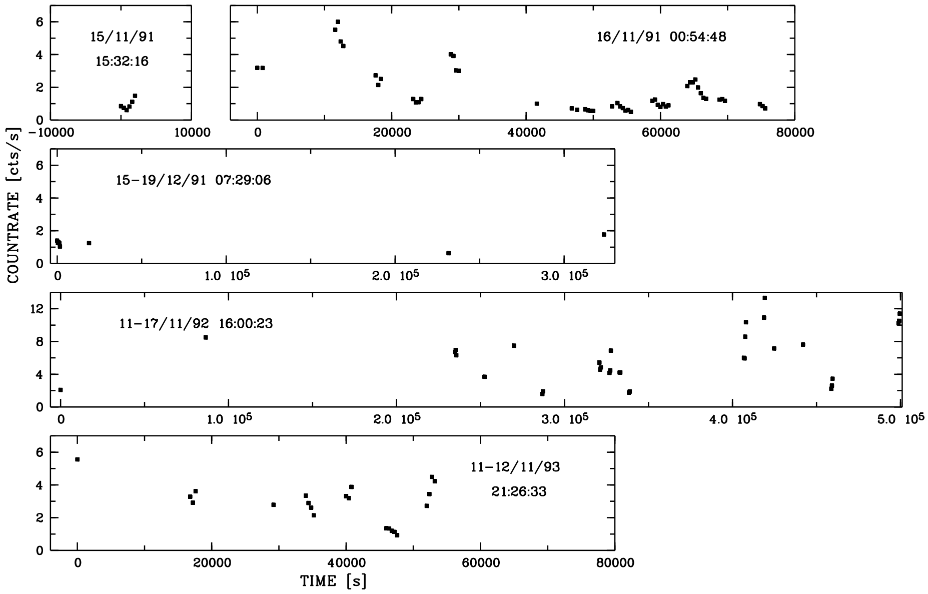

Figure 1. Long-term X-ray lightcurve of NGC 4051, based on all *ROSAT* PSPC observations. The source is variable by a factor $\sim$30 in count rate. The lightcurve of Nov. 16, 91 was earlier shown in McHardy et al. (1995), the one of Nov. 93 in Komossa & Fink (1997a). The time is measured in s from the beginnings of the individual observations.

4. Ultrasoft X-ray spectrum: 1E 0117.2-2837

This NLSy1 was discovered as an X-ray source by *Einstein* and is at a redshift of z=0.347 (Stocke et al. 1991). It is serendipituously located in one of the *ROSAT* PSPC pointings; the steep X-ray spectrum was briefly noted by Schwartz et al. (1993). When described by a single powerlaw continuum with Galactic cold column, the photon index is $\Gamma_{\rm x} \simeq -3.6$ (–4.3, if $N_{\rm H}$ is a free parameter). The source's count rate, 0.44 cts/s, is constant throughout the observation.

A successful description of the steep observed *ROSAT* spectrum is a warm-absorbed flat powerlaw of canonical index. We find a very large column density $N_{\rm w}$ in this case, and the contribution of emission and reflection is no longer negligible; there is also some contribution to Fe Kα. For the pure absorption model, the best-fit values for ionization parameter and warm column density are $\log U \simeq 0.8$, $\log N_{\rm w} \simeq 23.6$ ($N_{\rm H}$ is consistent with the Galactic value), with $\chi^2{}_{\rm red}$ = 0.74. Including the contribution of emission and reflection for 50% covering of the warm material gives $\log N_{\rm w} \simeq 23.8$ ($\chi^2{}_{\rm red}$ = 0.65).

Several strong EUV emission lines are predicted to arise from the warm material. Some of these are (Hβ refers to the warm-absorber-intrinsic value): FeXXIλ2304/H$\beta = 10$, HeIIλ1640/H$\beta = 16$, FeXXIλ1354/H$\beta = 37$, NeVIIIλ774/Hβ = 9, and, just outside the IUE sensitivity range for the given z, FeXXIIλ846/Hβ = 113. No absorption from CIVλ1549 and NVλ1240 is expected to show up in the UV spectrum. Both elements are more highly ionized.

Table 2. Log of *ROSAT* PSPC observations of NGC 4051 and warm-absorber fit results. $t_{\rm exp}$ = effective exposure time in s, CR = mean count rate in cts/s, L = *mean* (0.1–2.4 keV) luminosity corrected for cold and warm absorption.

date	$t_{\rm exp}$	CR	log U	log $N_{\rm w}$	$\Gamma_{\rm x}$	L [10^{41} erg/s]
Nov. 15, 1991	2705	1.0	0.2	22.52	-2.2	3.5
Nov. 16, 1991	28727	1.6	0.2	22.45	-2.2	5.4
Dec. 15 - 19, 1991	4783	1.0	0.1	22.35	-2.2	3.7
Nov. 11 - 17, 1992*	20815	6.0	0.2	22.35	-2.2	19.5
Nov. 11 - 12, 1993	12261	2.9	0.4	22.67	-2.3	9.5

* results of model fits uncertain due to off-axis location of source

5. Strong spectral variability: RX J0134.3-4258

This NLSy1 exhibited an ultrasoft spectrum in the *ROSAT* survey observation (Dec. 1990; formally $\Gamma_{\rm x} \simeq -4.4$). Interestingly, the spectrum had changed to flat in our subsequent pointed PSPC observation (Dec. 1992; $\Gamma_{\rm x} \simeq -2.2$). This kind of spectral variability is naturally predicted within the framework of warm absorbers, making the object a very good candidate for warm absorption.

We find that a warm-absorbed, intrinsically flat powerlaw can indeed describe the survey observation. Due to the low number of available photons, a range of possible combinations of U and $N_{\rm w}$ explains the data with comparable success. A large column density $N_{\rm w}$ (of the order 10^{23} cm^{-2}) is needed to account for the ultrasoft observed spectrum. The most suggestive scenario within the framework of warm absorbers is a change in the *ionization state* of ionized material along the line of sight, caused by *varying irradiation* by a central ionizing source. In the simplest case, lower intrinsic luminosity would be expected, in order to cause the deeper observed absorption in 1990, whereas the source is somewhat brighter in the survey observation (see Komossa & Fink 1997d for details). Some variability seems to be usual, though: the count rate changed by about a factor of 2 during the pointed observation (Fig. 2). If one wishes to keep this scenario, one has to assume that the ionization state of the absorber still reflects a preceding (unobserved) low-state in intrinsic flux. Alternatively, gas heated by the central continuum source may have *crossed the line of sight*, producing the steep survey spectrum, and has (nearly) disappeared in the 1992 observation. Finally, we note that an alternative explanation of the spectral variability in terms of a variable soft excess was suggested by Grupe (1996); see also Mannheim et al. (1996).

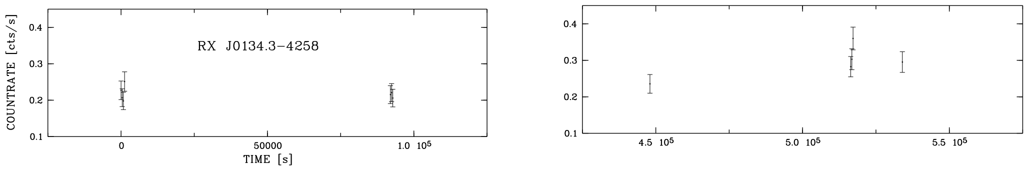

Figure 2. X-ray lightcurve of RX J0134-42 during the pointed *ROSAT* PSPC observation. The data were binned to time intervals of 400s.

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