AGN Outflows: Analysis of the Absorption Troughs

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Abstract. With the advent of Chandra and XMM, X-ray lines spectroscopy of AGN outflows is off to an exciting start. In this paper we illuminate some of the complications involved in extracting the outflow’s physical conditions (ionization equilibrium, total column density, chemical abundances) from such spectroscopic data. To do so we use the example provided by high-quality FUSE and HST observations of the outflow seen in NGC 985.

We show how simple determinations of the column density in the UV absorption lines often severely underestimate the real column densities. This is due to strong non-black saturation of the absorption troughs, where in many cases the UV line profile mainly reflects the velocity-dependent covering factor rather than the column density distribution. We then show that underestimating individual ionic column densities by a factor of 5 can cause a two orders of magnitude error in the inferred total column density of the outflow. In some case this will be enough to associate the UV and X-ray absorber with the same outflowing material.

Finally, we note that the UV spectra of NGC 985 have 10–20 times the resolution and 2–5× the S/N per resolution element compared with the best available Chandra spectra of similar objects. Therefore, in the X-ray band non-black saturation and velocity-dependent covering factor effects will only become abundantly clear using vastly more capable future X-ray telescopes. However, by taking into consideration the lessons learned from the UV band, we can greatly improve the quality of physical constraints we extract from current X-ray data of AGN outflows.

1. Introduction

Outflows in Seyfert galaxies are evident by resonance line absorption troughs, which are blueshifted with respect to the systemic redshift of their emission counterparts. Velocities of several hundred km s⁻¹ (Crenshaw et al. 1999; Kriss et al. 2000) are observed in UV resonance lines (e.g., C iv λλ1548.20,1550.77, N v λλ1242.80,1238.82, O vi λλ1037.62,1031.93 and Lyα), as well as in X-ray resonance lines (Kaastra et al. 2000; Kaspi et al. 2000). Similar outflows (often with significantly higher velocities) are seen in quasars that are the luminous relatives of Seyfert galaxies (Weymann et al. 1991; Korista Voit & Weymann 1993; Arav et al. 2001a). Reliable measurement of the absorption column densities in the troughs are crucial for determining the ionization equilibrium and abundances of the outflows, and the relationship between the UV and the ionized X-ray absorbers (Mathur et al. 1995; Elvis 2001).

In the last few years our group (Arav 1997; Arav et al. 1999a; Arav et al. 1999b; de Kool et al. 2001; Arav et al. 2001) and others (Barlow 1997, Telfer et al. 1998, Churchill et al. 1999, Ganguly et al. 1999) have shown that in quasar outflows most lines are saturated even when they are not black. We have also shown that in many cases the shapes of the troughs are almost entirely due to...
changes in the line of sight covering as a function of velocity, rather than to differences in optical depth (Arav et al. 1999b; de Kool et al. 2001; Arav et al. 2001a). As a consequence, the column densities inferred from the depths of the troughs are only lower limits.

These results have led us to suspect that many of the reported column densities in Seyfert outflows are likely underestimated. Recently, we have re-analyzed the HST high resolution spectroscopic data of the intrinsic absorber in NGC 5548 (Arav, Korista & de Kool 2002) and found that the CIV absorption column density in the main trough is at least four times larger than previously determined. Furthermore, we have shown that similar to the case in quasars, the shape of the main trough is almost entirely due to changes in covering fraction as a function of velocity, and is not due to differences in real optical depth.

In this paper we analyze the outflow in another Seyfert 1 galaxy, NGC 985. Similar to the NGC 5548 case, the apparent column density (Lyα in this case) is a severe underestimate of the real column density. Furthermore, the resulting errors in the inferred values of the total hydrogen column density (N_H) and the ionization parameter (U) of the absorbing gas are far larger. For the specific case of NGC 985, the real N_H and U values may allow the X-ray and UV absorbers to arise from the same gas. We conclude by highlighting potential difficulties expected in the X-ray spectral analysis of AGN outflows, based on the UV investigation shown here and elsewhere.

2. The case of NGC 985

NGC 985 is a bright (V = 13.8 for UV see Fig 1) X-ray: < F_2−10 keV > = 2 × 10^{-11} ergs, Nicastro et al. 1998), nearby Seyfert 1 galaxy, which shows a strong and complex system of warm absorbers (N_H = 10^{22} and 10^{23} cm^{-2}) in its ROSAT-PSPC (Brandt et al. 1995) and ASCA (Nicastro et al. 1998). In figure 1 we show the available HST data of the intrinsic UV absorber in NGC 985, which covers the Lyα and N_v troughs. To find the physical conditions of the absorbing gas we first extract the apparent column densities for the Lyα and N_v troughs for the outflow, and then use these values to compute the N_H and U of the absorbing gas.

2.1. Apparent column density extraction and the resultant ionization equilibrium determination

Figure 2 shows an unsaturated absorption model for the Lyα trough consisting of an unabsorbed emission model convolved with six Gaussian absorption components. The fit is very good and the main discrepancy (seen around 1266 Å) is due to our restrictive assumption that each kinematic component for Lyα and N_v will have the same velocity centroid. We note in passing that this assumption holds quite well in this case, since four of the Lyα components are fitted very well using the velocity centroid of the N_v components. For absorption component 4, the Gaussian parameters yield log(N_H I) = 14.

Figure 3 shows an unsaturated absorption model for the N_v doublet. We vary the Gaussian parameters to match the absorption in the blue doublet component and then scaled their depth by half to model the absorption in the red doublet component.
(or only slightly so) since their depths in the red and blue doublet lines are consistent with the expected 1:2 optical depth ratio (the ratio of their oscillator strengths). For absorption component 4, the Gaussian parameters yield \( \log(N_{\nu}) = 14.2 \).

It is usually assumed that the plasma is in photoionization equilibrium and therefore the relevant physical parameters are the total hydrogen column density \((N_H)\) and the ionization parameter \((U)\) of the absorbing gas. In order to determine these we use the photoionization code CLOUDY (Ferland 1996) to try to find combinations of these parameters which will reproduce the measured column densities.

![Fig. 4. Ionization parameter \( U \) and total column density \( N_H \) for component 4 in the NGC 985 outflow, based on the apparent column densities extracted from the fits shown in figures 2 and 3. All quantities are shown in log form.](image)

In figure 4 we show photoionization solutions for absorption component 4. The presentation method is based on the grid models approach developed in Arav et al. (2001b), using the same ionizing continuum. We plot curves of constant \( N_{\text{ion}} \) (determined from the observed troughs) in the \( N_H/U \) plane. That is, within the range of plotted parameters, any combination of \( N_H \) and \( U \) that falls on the curve yields the desired column density value (for an assumed set of elemental abundances, solar in our case). The parameters of the absorber are determined by the crossing of the different \( N_{\text{ion}} \) curves. We note that with two given curves we can obtain two solutions, since two crossing points are possible. By coincidence, we obtained a single solution in this particular case. The inferred \( N_H \) is at least two orders of magnitude too small to account for a typical warm absorber column density (Kaastra et al. 2000; Kaspi et al. 2000).

### 2.2. Non-black saturation

![Fig. 5. Modeling the Ly\( \beta \) absorption with the same six Gaussians absorption-model used in modeling the Ly\( \alpha \) trough (see Fig. 2). The upper dotted line is based on assuming no saturation in Ly\( \alpha \). That is, the maximum optical depth of each component was multiplied by the ratios of oscillator strength and wavelength for Ly\( \beta \) and Ly\( \alpha \), that is by \([f\lambda]_{\text{Ly}\beta}/[f\lambda]_{\text{Ly}\alpha}\). The poor fit in all components is indicative of saturation in Ly\( \alpha \). The lower dotted line is an absorption model assuming full Ly\( \alpha \) saturation (i.e., using the same Gaussians with no scaling); moderate saturation is evident in components 4, 5 and 6 and small saturation is inferred for components 2 and 3.](image)

However, our ionization equilibrium inferences are crucially dependent upon the reliability of the \( N_{\nu} \) and Ly\( \alpha \) column densities inferred from our absorption models (Figs. 2 and 3). The evidence we have collected over the last few years suggests that it is impossible in principle to extract a reliable column density from one singlet line (see § 1 and Arav et al. 2002). It is therefore quite possible that our Ly\( \alpha \) inferred H\( I \) column density is greatly underestimated. Luckily we possess FUSE spectra that covers the Ly\( \beta \) and Ly\( \gamma \) outflow troughs in NGC 985, and can directly check the reliability of the Ly\( \alpha \) model.

Figure 5 shows the results of applying the Ly\( \alpha \) absorption model to the Ly\( \beta \) trough. Our very good model-fit for the Ly\( \alpha \) trough (Fig. 2) fails completely when we apply it to the Ly\( \beta \) trough assuming no saturation (upper dotted line). A model assuming complete saturation (lower dotted line) fits the data considerably better, but since it over-predicts the depth of the troughs we determine
Fig. 6. Similar to Fig. 4 showing the ionization equilibrium solutions for both the real (solid line) and apparent (dashed line) H\textsc{i} column density. The apparent H\textsc{i} column density was extracted from the HST/STIS data alone assuming no saturation, while the real H\textsc{i} column density that is five times larger than the apparent one is based on the FUSE data. A factor 5 difference in the H\textsc{i} column density increases the inferred total absorber column density by more than two order of magnitudes. We note that the lower crossing-point solution (the one without the dot) can be excluded, since we do not detect absorption from low ionization species that would be present in that case.

that the Ly\textbeta is not heavily saturated. This conclusion is confirmed by the shape of the Ly\gamma trough where all the components except number 6 are significantly shallower. The apparent H\textsc{i} column density of component 4, as measured from the Ly\alpha trough, is 5\times smaller than its real H\textsc{i} column density deduced with the constraints imposed by the Ly\beta and Ly\gamma troughs. In passing, we mention that the FUSE spectra also show saturation in the O\textsc{vi} lines.

3. Realistic ionization equilibrium

Figure 6 illustrates the consequence of ignoring the possibility of saturation in Ly\alpha and therefore underestimating the H\textsc{i} column density in component 4 by a factor of five. The physical solution that uses the real H\textsc{i} column density results in an absorber with 100\times higher $N_H$ and roughly a 10\times higher ionization parameter than the one using the apparent column density. The relative difference between the two solutions is a robust key point of this investigation. Absolute values of the correct $N_H$ and $U$ are far less accurate due to the systematic uncertainties in chemical abundances and incident ionizing spectrum, as well as the reliance on only to ionic column densities. Nonetheless, we point out that the solution based on realistic H\textsc{i} column density is compatible with physical parameters inferred for warm absorbers in general (Kaastra et al. 2000; Kaspi et al. 2000), while the apparent one is much too low in both $N_{\text{ion}}$ and $U$.

4. Summary and Relevance to analyses of X-ray warm absorbers data

1. Non-black saturation is prevalent in UV troughs of AGN outflows, even when the trough is fully resolved spectroscopically. This suggests that the same phenomenon occur in the X-ray troughs of the same objects. In addition, a single covering fraction per absorption component is a poor approximation, since covering fraction is often strongly velocity-dependent.

2. Errors in column density estimates can be greatly amplified in the inferred ionization equilibrium for the absorbing gas. In the case of component 4 in NGC 985, correcting the $N_{\text{H\textsc{i}}}$ by a factor of five resulted in a two orders of magnitude higher $N_H$ and an order of magnitude higher $U$. These differences are large enough to make UV component 4 compatible with being the same gas as the X-ray warm absorber.

3. Many line series are covered by the X-ray band, thus allowing for excellent saturation diagnostics and thus the extraction of reliable column densities. However, care must be taken to allow for non-black saturation, which is very different from saturation due to spectroscopically unresolved absorption components.

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