CONTRASTING THE ULTRAVIOLET AND X-RAY O vi COLUMN DENSITY INFERRED FOR THE OUTFLOW IN NGC 5548

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ABSTRACT

We compare X-ray and UV spectroscopic observations of NGC 5548. Both data sets show O vi absorption troughs associated with the active galactic nuclei outflow from this galaxy. We find that the robust lower limit on the column density of the O vi X-ray trough is 7 times larger than the column density found in a study of the O vi UV troughs. This discrepancy suggests that column densities inferred for UV troughs of Seyfert galaxy outflows are often severely underestimated. We identify the physical limitations of the UV Gaussian modeling as the probable explanation of the O vi column density discrepancy. Specifically, Gaussian modeling cannot account for a velocity-dependent covering fraction, and it is a poor representation for absorption associated with a dynamical outflow. Analysis techniques that use a single covering fraction value for each absorption component suffer from similar limitations. We conclude by suggesting ways to improve the UV analysis.

Subject headings: galaxies: active — galaxies: individual (NGC 5548) — galaxies: nuclei — galaxies: Seyfert

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 both UV resonance lines (e.g., C iv \(\lambda\lambda1548.20, 1550.77\), N v \(\lambda\lambda1238.82, 1242.80\), O vi \(\lambda\lambda1031.93, 1037.62\), and Ly\(\alpha\)), 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, which are the luminous relatives of Seyfert galaxies (Weymann et al. 1991; Korista et al. 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.

NGC 5548 is one of the most studied Seyfert galaxies, including intensive reverberation campaigns (Netzer & Maoz 1990; Clavel et al. 1991; Peterson et al. 1991; Korista et al. 1995), line studies (Krolik et al. 1991; Ferland et al. 1992; Goad & Koratkar 1998; Kaspi & Netzer 1999; Korista & Goad 2000), and theoretical modeling (Done & Krolik 1996; Bottorff, Korista, & Shlosman 2000; Srianand 2000). The intrinsic absorber in NGC 5548 was studied in the UV using the International Ultraviolet Explorer (Shull & Sachs 1993), the Hubble Space Telescope (HST) Goddard High Resolution Spectrograph (GHRS) (Mathur, Elvis, & Wilkes 1999) and Space Telescope Imaging Spectrograph (STIS) (Crenshaw & Kraemer 1999), the Far Ultraviolet Spectroscopic Explorer (FUSE) (Brotherton et al. 2002), and in X-ray with the ASCA (George et al. 1998) and Chandra (Kaastra et al. 2000, 2002) satellites. These high-quality observations, combined with the relative simplicity of its intrinsic absorption features, make NGC 5548 an excellent target for understanding the nature of Seyfert outflows.

In the last few years our group (Arav 1997; Arav et al. 1999a, 1999b, 2001a; de Kool 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 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. 1999a, 2001a; de Kool et al. 2001). Gabel et al. (2003) show the same effect in the outflow troughs of NGC 3783. 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 the current determination of column densities in Seyfert outflows is highly uncertain. Recently, Arav, Korista, & de Kool (2002) have reanalyzed the HST high-resolution spectroscopic data of the intrinsic absorber in NGC 5548 and found that the C iv absorption column density in the main trough is at least 4 times larger than previously determined. Furthermore, in the same paper it was shown that similar to the case in quasars, the shape of the main trough is almost entirely due to changes in the covering fraction as a function of velocity and is not due to varying column density as a function of velocity.

An important new saturation diagnostic is available in the form of UV and X-ray absorption troughs that arise from the same ion. The relationship between the ionic column density \(N_{\text{ion}}\) and the optical depth \(\tau\) of an absorption trough is given by (see eq. [3] in Arav et al. 1999b)

\[
N_{\text{ion}} = \frac{3.8 \times 10^{14} \text{ cm}^{-2}}{\lambda_0 f_k} \int \tau(v) dv ,
\]

where \(\lambda_0\) and \(f_k\) are the wavelength and oscillator strength of the transition, respectively, and \(v\) is the velocity in km s\(^{-1}\).
Using the apparent optical depth \( I = e^{-\tau} \), where \( I \) is the residual intensity) in equation (1), a trough with the same \( I(v) \) yields 50 times higher \( N_{\text{ion}} \) for an X-ray line as compared with a UV line with the same \( f_{\text{ik}} \), simply because its wavelength is 50 times smaller. In cases where the UV trough is saturated and its shape is determined by changes in covering fraction as a function of velocity, it is virtually impossible to distinguish between \( \tau \) values above \( \sim 3 \) (see Arav et al. 2002). For equal oscillator strength, the X-ray trough of the same ion will have \( \tau = 1 \) when the UV trough reaches \( \tau_{\text{UV}} = 50 \). Therefore, the X-ray trough is sensitive to a much higher column density than that of the UV and can provide a crucial saturation diagnostic for the UV troughs.

In this paper we compare the \( \text{O} \text{VI} \) column density inferred independently from UV and X-ray absorption features in the spectrum of NGC 5548 and demonstrate the large discrepancy between the two values. The X-ray–derived \( \text{O} \text{VI} \) column density is 7 times larger than that of the UV. Since the X-ray determination is a robust lower limit, we conclude that the UV lines are much more saturated than originally inferred and identify the UV analysis as the probable cause for this discrepancy. Specifically, Gaussian modeling cannot account for a velocity-dependent covering fraction, and more generally Gaussian modeling is a poor representation for absorption associated with a dynamical outflow.

2. CONTRASTING THE UV AND X-RAY–INFERRRED \( \text{O} \text{VI} \) COLUMN DENSITY

2.1. Data Description

NGC 5548 was observed by \textit{FUSE} on 2000 June 7 with a total exposure time of 25 ks. A full description of the observations, reduction process, and plots of the spectra are presented in Brotherton et al. (2002). These observations include the spectral region associated with both the emission and absorption features of the \( \text{O} \text{VI} \lambda\lambda 1032, 1038 \) doublet in the rest frame of NGC 5548.

Our \textit{XMM-Newton} data were taken on 2001 July 12. The total exposure was 116 ks, and the data were reduced using the standard Science Analysis System analysis package. Here we only discuss the reflection grating spectrometer (RGS) spectra. A detailed description of the RGS instruments is given by den Herder et al. (2001). Briefly, there are two almost identical RGS detectors on board the \textit{XMM-Newton} that cover the 5–38 Å range with an almost uniform spectral resolution of 0.05 Å and have a maximum effective area of about 140 cm\(^2\) at 15 Å. In the present work we focus on the \( \text{O} \text{VI} \) line region around 22 Å. Due to the failure of one of the nine CCDs of RGS2, only data from RGS1 are available in this wavelength band and analyzed here. The spectrum was fitted using a continuum plus absorption components, as described by Kaastra et al. (2002). A full analysis of the spectrum will be given elsewhere (Steenbrugge, Kaastra, & Edelson 2003), as well as timing analysis of the data (Markowitz et al. 2002) and analysis of the European Photon Imaging Camera (EPIC) data (Pounds et al. 2003).

2.2. \( \text{O} \text{VI} \) Column Density Extractions

In the \textit{XMM-Newton}/RGS spectrum there is a distinct absorption line visible at a rest wavelength of 22.0 Å due to \( \text{O} \text{VI} \) (see Fig. 1). The line occurs in the wavelength range of the well-known He-like triplet of \( \text{O} \text{VII} \), from which the forbidden line at 22.1 Å and the intercombination line at 21.8 Å are seen in emission, and the resonance line at 21.6 Å is seen in absorption (cf. Kaastra et al. 2002). The \( \text{O} \text{VI} \)

![Fig. 1. — \textit{XMM-Newton}/RGS data of NGC 5548. The absorption trough at 22.0 Å is due to the \( \text{O} \text{VI} \) transitions discussed in the text.](image-url)
absorption line at 22.0 Å is in fact a satellite to these He-like lines, and its importance for active galactic nuclei (AGN) spectra was first recognized by Pradhan (2000). The line (in fact an unresolved blend of the so-called r and u lines) is caused by inner-shell photoexcitation of an O VI ion in the ground state to the 1s2p(3P)2s−2P1/2 and 1s2p(3P)2s−2P3/2 levels, respectively. We used atomic data for this transition as calculated by Behar & Kahn (2002). The wavelength for the blend of the two components is 22.007 Å, and the combined oscillator strength f is 0.525 (Pradhan gives 22.05 Å and f = 0.576).

The equivalent width of this O VI trough is 40 ± 10 mA, and therefore a lower limit for the associated column density is 3.2 ± 0.8 × 10^{16} cm^{-2}, where the error is directly associated with the signal-to-noise ratio of the data. A detailed description of the fitting method used to extract this O VI column density value is given in Steenbrugge et al. (2003).

We stress that this is a lower limit since (1) there may be unresolved absorption components due to the R = 500 resolution of the RGS at this wavelength; (2) the trough may show nonblack saturation even for resolved components, similar to the situation evident in the UV troughs associated with the outflow; and (3) the adjacent O VI f emission line can partly fill in the O VI trough. We note that the FWHM of the O VI trough is 800 ± 200 km s^{-1} and that its centroid velocity is −370 ± 160 km s^{-1} for a systemic redshift of z = 0.017175 (see redshift discussion in Brotherton et al. 2002).

Brotherton et al. (2002) analyzed the FUSE spectra of NGC 5548 in order to determine the O VI absorption column density from the O VI λλ1031.93, 1037.62 (oscillator strength of 0.13 and 0.066, respectively; Verner, Verner, & Ferland 1996). They used the program SPECFIT (Kriss 1994) to fit the O VI spectral region using the following assumptions: approximating the intrinsic absorption as several components with Gaussian distributions in optical depth that are permitted to partially cover the background source, where the optical depth ratio of the doublets is constrained to be 2:1 at all velocities. They have looked at two types of models: one in which the outflow covers all the emission components (continuum, broad emission lines, and narrow emission lines [NELs]), and one in which the flow does not cover the NELS. Since the model with uncovered NELS gives higher N_{O VI} estimates, we will concentrate on it, noting that our discussion is similarly applicable to the other model.

The overall quality of the Brotherton et al. (2002) fit is very good (see their Fig. 3), and the statistical error quoted for the N_{O VI} associated with each of the absorption components is mostly between 10% and 20% (their Table 2). We note, however, that their model includes 43 free parameters: eight absorption Gaussians with four free parameters each (position, depth, width, and covering fraction), three emission Gaussians with three free parameters each (position, height, and width), and two free parameters for the continuum (flux and slope). Although the goodness of the fit is impressive, it is not surprising given the number of free parameters involved. Summing up the N_{O VI} determinations in each component we obtain a total N_{O VI} = 4.9 ± 0.6 × 10^{15} cm^{-2}, where for a conservative error estimate we simply added the quoted individual errors. The total width of the O VI UV absorption complex is ~1200 km s^{-1}, which is consistent with the width of the O VI X-ray trough (see above).

We therefore possess two very different estimates for the O VI absorption column density associated with the outflow in NGC 5548. On the one hand, the XMM-Newton/RGS observation gives a lower limit N_{O VI} ≥ 3.2 ± 0.8 × 10^{16} cm^{-2}; on the other hand, a Gaussian fitting of the FUSE data yields N_{O VI} = 4.9 ± 0.6 × 10^{15} cm^{-2}.

2.3. Kinematic Distribution of the X-Ray–inferred O VI Column Density

At 22 Å the resolution element of the RGS instrument is roughly 700 km s^{-1}. In order to obtain the deep O VI absorption trough seen in the data (Fig. 1), the absorbing material must therefore be spread over a similar velocity interval. An absorption component with a much narrower velocity width cannot account for the X-ray trough even if its optical depth is very high. This narrow yet deep intrinsic trough will be transformed into a shallow trough of roughly 700 km s^{-1} width by the line-spread function of the instrument.

Brotherton et al. (2002) measured FWHM < 150 km s^{-1} for UV components 2–6 of the outflow. Therefore, the high X-ray–inferred N_{O VI} cannot be hidden in only one, two, or three of these components even if they are highly saturated. UV components 0.5 and 1 are wider (350 and 280 km s^{-1}, respectively). However, even combined, these components cannot account for the X-ray–inferred N_{O VI} by themselves. Their combined width and shape are not enough to produce the observed X-ray trough even if we assume that both components are highly saturated. We conclude that since the X-ray–inferred N_{O VI}, must be associated with the UV O VI kinematic components, at least half of these components have to be highly saturated to allow for the observed X-ray O VI absorption trough.

3. WHAT CAUSES THE DISCREPANCY IN THE O VI COLUMN DENSITY DETERMINATIONS?

3.1. The Plausibility of Real Temporal Changes

A difference of 13 months exists between the FUSE (2000 June 7) and XMM-Newton (2001 July 12) observations of NGC 5548. It is therefore important to address the possibility that the order-of-magnitude difference in inferred N_{O VI} is caused by temporal changes. In Table 1 we list the relevant UV and X-ray observations, including the continuum flux associated with each. Based on the four available

| Epoch       | Instrument | Flux            | Reference |
|-------------|------------|-----------------|-----------|
| 1996 Aug.... | HST/GHRS   | 5.6 × 10^{-14}  | 1         |
| 1998 Mar.....| HST/STIS   | 6.6 × 10^{-14}  | 1         |
| 1999 Dec.....| Chandra/LETGS | 4.0 × 10^{-14} | 2         |
| 2000 Jun.....| FUSE       | 1.5 × 10^{-14}  | 3         |
| 2001 Jul.....| XMM-Newton/RGS | 5.0 × 10^{-14} | 4         |
| 2002 Jan.....| Chandra/LETGS | 2.6 × 10^{-14} | 5         |
| 2002 Jan.....| HST/STIS   | 2.0 × 10^{-14}  | 1         |

* Indicates F_{21} at 1360 Å in units of ergs s^{-1} cm^{-2} Å^{-1}.

b Flux in the 2–10 keV band in units of ergs s^{-1} cm^{-2}.

c Average F_{21} between 1110 and 1150 Å in units of ergs s^{-1} cm^{-2} Å^{-1}.

REFERENCES.—(1) Crenshaw et al. 2003; (2) Kaastra et al. 2002; (3) Brotherton et al. 2002; (4) Pounds et al. 2003; (5) Kaastra et al. 2003.
epochs of high-resolution UV spectroscopy of the object, we conclude that strong variations in the shape and strength of the UV troughs over a 1 yr timescale are unlikely. Components 2, 4, and 5 of the C iv trough (following Crenshaw & Kraemer 1999) show only marginal changes in the three available epochs of high-resolution spectroscopy: the HST/GHRS spectrum taken in 1996 August 24 (Mathur et al. 1999), the HST/STIS observation from 1998 March 11 (Crenshaw & Kraemer 1999), and the HST/STIS observation from 2002 January 22 (D. M. Crenshaw et al. 2003, in preparation). Only components 1 and 3 (which are blended to some extent) show significant variation (at the ~50% level). The main C iv trough (component 4) showed less than 10% changes in residual intensity between all three epochs. Furthermore, component 4 in the C iv trough is almost identical in shape and depth to the main component in the O vi trough covered by the FUSE observations (see Fig. 4 in Arav et al. 2002). Such similarity argues for both small temporal variation in the troughs, as well as for a moderate-to-high degree of saturation in both the C iv and O vi troughs (see discussion in Arav et al. 2002). These comparisons suggest that the shape of the main UV troughs in NGC 5548 change rather moderately on a timescale of 2–6 yr.

We note that if the UV troughs show nonblack saturation, large column density changes are possible even when the absorption troughs do not change appreciably. However, UV analysis techniques (Gaussian modeling or otherwise) have a limited dynamical range for inferring real optical depth (see §3.3). Therefore, if the trough’s shape did not change appreciably it is very difficult to deduce a real change in the O vi absorbing column density even if the level of saturation increased considerably. Furthermore, the X-ray data suggest that dramatic N_{O vi} changes are unlikely over a 1 yr timescale.

Recently (2002 January), a very long Chandra Low Energy Transmission Grating Spectrometer (LETGS) observation (340 ks) of NGC 5548 was obtained (J. S. Kaasra et al. 2003, in preparation). Preliminary analysis indicates that the detected O vi trough is very similar to the one seen in the XMM-Newton/RGS observation. Such an occurrence suggests that an order-of-magnitude change in the EW of the O vi X-ray trough between the FUSE (2000 June 7) and XMM-Newton (2001 July 12) observations of NGC 5548 is unlikely. There is also an earlier epoch Chandra LETGS observation taken in 1999 December (86 ks; Kaasra et al. 2000) that has been reanalyzed using improved wavelength and effective area calibration by Kaasra et al. (2002). The S/N of this observation is significantly lower than the S/N of either the XMM-Newton data (shown here) or the new Chandra LETGS observation. The O vi line is marginally detected (Fig. 3 in Kaasra et al. 2000), with a 1σ upper limit of 3.4 × 10^{16} cm^{-2}, which is consistent with the XMM-Newton measurement.

Additional support for relatively small changes in the O vi X-ray trough on a year timescale comes from comparing total fluxes in the 2–10 keV bands. The X-ray flux dropped by roughly 50% between the two higher quality observations (XMM-Newton and 2002 January Chandra), yet the derived N_{O vi} values are similar in both observations. This occurrence suggests that the N_{O vi} value is quite insensitive to considerable flux changes over a 1 yr timescale.

3.2. Validity of the Underlying Physical Model

The modeling of the absorption troughs presented in Brotherton et al. (2002) is the most sophisticated and detailed Gaussian fitting of an AGN outflow to date. As mentioned above, the “goodness” of their fit is impressive. It is clear that a Gaussian fitting algorithm can obtain a low χ^2 fit between the data and a model spectrum. However, after obtaining a good fit the important question is: how physically valid is the Gaussian fitting process? In other words, how well would the absorption column densities determined from Gaussian components represent the actual column densities of the AGN outflow?

Gaussian fitting is a common analysis tool for spectral absorption features. In particular, it is used in interstellar medium (ISM) and intergalactic medium (IGM) studies. In these environments a Gaussian distribution of optical depth as a function of velocity seems physically plausible. This is because there is little dynamics involved, and therefore, a thermal velocity distribution function yields a Gaussian optical depth function (even if “turbulent” broadening is invoked to explain the larger-than-thermal width). Furthermore, for ISM and IGM the geometrical sizes of the absorption clouds are much larger than the emission sources they cover. Therefore, the assumption that along our line of sight the absorber covers the emission source completely and uniformly is very reasonable.

When these models are adapted to represent AGN outflows two ingredients are added: a constant covering fraction to allow for partial line-of-sight covering of the emission source, and a Gaussian velocity width much larger than what is found for ISM and IGM clouds (in order to account for the width of the outflow’s absorption features). The physical applicability of both ingredients is highly questionable; first, careful analysis of high-resolution, high S/N spectra of AGN outflows reveals that the covering fraction is a strong function of velocity (Arav et al. 1999a; de Kool et al. 2001; Gabel et al. 2003). In particular, this is also the situation we find for the C iv trough of NGC 5548 (Arav et al. 2002). The strong dependence of the covering fraction on velocity naturally undermines the constant covering fraction assumption.

Similarly, the large Gaussian velocity width invoked to fit the outflows features is also problematic. For acceptable photoionization equilibria, clouds’ thermal widths are ≲20 km s^{-1}. For IGM clouds a “turbulent” broadening is invoked to explain the larger-than-thermal width. However, the FWHM of this broadening is rather small (typical values for the Doppler parameter are b ≈ 16–46 km s^{-1}; Sembach et al. 2001) and is associated with motions on scales of hundreds of kiloparsecs. In contrast, the FWHM of Gaussian absorption components in the Brotherton et al. (2002) modeling reaches 350 km s^{-1} and is associated with length scales of several parsecs at most. The larger FWHM and the much smaller length scales associated with the AGN outflow weakens the physical plausibility of Gaussian optical depth distribution, as compared with the IGM case. We conclude that there is little physical basis for modeling outflow troughs as Gaussians clouds with a constant covering fraction.

Both the strong dependence of the covering fraction on velocity and the large width of the outflow absorption features can be simply accounted for by appealing to the dynamical nature of the outflow. Whereas it is reasonable to
expect that a cloud will have a single covering factor (although see de Kool et al. 2002), this is not the situation for an outflow, in which the covering factor can be a strong function of velocity. Toy models that illustrate these kinematic/geometric effects are found in Arav (1996) and Arav et al. (1999b). A similar picture arises in global models for the structure of AGN (Elvis 2000, 2002).

3.3. Asymmetric Errors Associated with the Extraction of Column Densities

Another important issue is the estimate of errors associated with the extraction of column densities from the absorption troughs. A formal statistical error from minimizing the \( \chi^2 \) between the data and a model spectrum based on a prescribed \( \tau(v) \) can greatly underestimate the real column density errors. For example, let us assume that at a given point the covering fraction is exactly 0.5. In this case \( I = 0.5 + e^{-\tau} \), where \( I \) is the residual intensity and \( \tau \) is the optical depth. Assuming \( I = 0.531 \), we obtain from the above relationship \( \tau = 3.5 \). However, even a very small \( \Delta \tau = 0.03 \) error will cause the following error in optical depth, \( \tau = 3.5^{\pm 0.05} \), and of course if \( \Delta \tau = 0.031 \), the formal error will be \( \tau = 3.5^{\pm 0.08} \). An error of \( \Delta \tau = 0.03 \) corresponds to a \( S/N = 30 \), which is rarely (if ever) achieved for high-resolution UV spectroscopy of AGN outflows. We therefore conclude that when the derived optical depth value is above 3 it is virtually impossible to set a meaningful positive error estimate. In such cases we should simply acknowledge that the derived optical depth value is a lower limit.

One can argue that a proper error analysis based on minimizing \( \chi^2 \) should also yield the \( \tau = 3.5^{\pm 0.05} \) result. However, this is only correct for one resolution element. Once we use a prescribed \( \tau(v) \) to fit a full trough, we lose our ability to distinguish between highly saturated regions in the trough and less saturated ones. The formal \( \chi^2 \) error will be obtained from averaging over the entire trough, whereas in some parts of the trough the actual error can be very large and dominate the derived column density error. This situation is accentuated when the shape of the trough is dominated by a velocity-dependent covering fraction and not by \( \tau(v) \) variations.

For example, absorption component 4 in the Brotherton et al. (2002) modeling has a maximum optical depth of 7 in the blue doublet component (extracted from the parameters in their Table 2 and using their eqs. [1] and [2]) and, therefore, a maximum optical depth of 3.5 in the red doublet component. Based on the analysis presented above, it is possible that the real optical depth in this absorption component is far larger.

3.4. Different Continuum-emitting Regions in the X-Ray and UV

For \( \text{O}\, \text{vi} \) the relevant UV continuum is near 1030 Å, whereas that of the X-ray continuum is near 20 Å. It is plausible that the size and/or location of the emitting region at these wavelengths is quite different. It is possible that the outflow may cover different fractions of the continuum source, depending on the wavelength. Such differences will complicate the comparison between UV and X-ray–determined absorption column density of the same ion. Unfortunately, little is yet understood about the continuum-emitting mechanism(s) in AGNs. Thus, we cannot quantify the effects expected from the difference in the respective emitting regions.

However, in the context of the current investigation the important question is whether size/location differences in the emitting regions can explain the discrepancy between the UV- and X-ray–inferred \( \text{O}\, \text{vi} \) column densities. Two combined characteristics of the NGC 5548 \( \text{O}\, \text{vi} \) absorber lead us to conclude that such an outcome is not plausible. First, the velocity width and the overall depth of the \( \text{O}\, \text{vi} \) UV and X-ray absorption troughs are quite similar. Second, we are comparing an apparent \( \text{O}\, \text{vi} \) X-ray column density (derived from eq. [1] using the apparent optical depth, i.e., assuming no saturation) with the inferred real UV \( \text{O}\, \text{vi} \) column density (which should account for saturation effects). It is easy to hide a large column density in a saturated trough (saturation in partially covering components or in unresolved components), but it is difficult to decrease the lower column density limit for a given trough’s shape. For example, if the covering fraction of the X-ray trough is much larger than the UV one, then the apparent X-ray column is larger than the apparent UV column. However, in that case we should observe a much deeper X-ray trough compared with the UV one, which is not seen in the NGC 5548 data. We conclude that it is unlikely that different UV and X-ray–emitting region geometry will allow the apparent X-ray column density to be an order of magnitude larger than the real UV column density. Moreover, the striking kinematic similarity of the Ly\( \beta \) UV trough and the \( \text{O}\, \text{vi} \) X-ray troughs in NGC 3783 (see Fig. 2 in Gabel et al. 2003) strongly suggests that a large overlap exists between the X-ray and UV continuum-emitting regions along our outflow-intersecting line of sight.

We note, however, that the argument can be turned around. A detailed comparison of X-ray and UV absorption troughs rising from the same ion may give us an important handle on the geometries of these different emitting regions. However, such a comparison necessitates higher quality X-ray data than those described here.

4. DISCUSSION

The \( \text{O}\, \text{vi} \) data in the NGC 5548 \textit{FUSE} observation have a \( S/N \approx 10 \) (Brotherton et al. 2002). Such limited \( S/N \) data do not allow a direct determination of the covering fraction and optical depth as a function of velocity. This forces the modeler to use some combination of physically weak assumptions; in descending order of “weakness” these are the following:

1. The apparent optical depths are equal to the real ones.
2. The optical depth is assigned a prescribed function (normally a Gaussian).
3. Each component of the flow is given a single covering fraction value, ignoring the possibility of velocity-dependent covering.

Higher \( S/N \) observations are therefore needed in order to avoid the practical necessity of using these assumptions.

We point out that a careful solution of the optical depth and covering fraction as a function of velocity (using doublet lines; e.g., Arav et al. 2002) can greatly increase the dynamical range for \( \tau \) determination. Using the example from § 3.3, an \( I = 0.531 \) gives \( r_{\text{apparent}} = 0.6 \). Solving for \( \tau \) using the doublet equations can yield robust estimates up to \( \tau = 3 \) in the weak doublet component, or \( \tau = 6 \) in the strong
one, which increases our dynamical range for $\tau$ determination by an order of magnitude. Furthermore, even in cases of higher saturation, lower limits for $\tau$ and hence for $N_{\text{ion}}$ are useful in constraining the physical conditions of the absorber, provided we acknowledge that these are indeed lower limits (see the case of BALQSO PG 0946+301; Arav et al. 2001b).

Finally, in view of the caveats described in this paper, we advocate the following cautious recipe for determining column densities from absorption troughs of AGN outflows:

1. For a singlet line, with no other observed lines from the same ion, we can only measure the apparent optical depth as a function of velocity and use the resultant integrated column density as a lower limit. This is because it is conceptually impossible to decouple the effects of optical depth from those of covering factor for a single line. In particular, this is the case for Ly$\alpha$ in the HST/STIS band.

2. For a doublet line we can solve for both the optical depth and the covering fraction as a function of velocity. For this we need a sufficiently narrow absorption complex so that absorption features from the two doublet components do not blend. If blending occurs, we have to resort to apparent optical depth estimates. Furthermore, for the unblended case, if the derived optical depth values are larger than $\sim 3$ for the weak doublet component, we have to establish a realistic lower limit (based on the S/N and emission models' uncertainties), which in practice will never be much higher than $\tau \sim 3$.

3. A line series from the same ion offers the best column density diagnostics because of the large spread in oscillator strength values. Most important in this regard is the Lyman series. A modest S/N coverage of several of these lines allows for a simple and accurate determination of $N_{\text{H}}$. A similar situation occurs in the X-ray band, where many of the observed ions are H- or He-like and therefore show the corresponding line series.

5. SUMMARY

X-ray and UV spectra of NGC 5548 show O vi absorption troughs associated with the AGN outflow from this galaxy. A lower limit on the column density of the O vi X-ray trough is an order of magnitude larger than the column density found by Brotherton et al. (2002) using Gaussian modeling of the O vi UV troughs.

It is unlikely that the discrepancy in the inferred $N_{\text{O vi}}$ reflects actual changes in the O vi absorption between the epochs of the X-ray and UV observations. Instead, we interpret the discrepancy as additional evidence that column densities inferred for UV troughs of Seyfert outflows are often severely underestimated. We identify the physical limitations of Gaussian modeling as the probable explanation of the $N_{\text{O vi}}$ discrepancy. Specifically, Gaussian modeling cannot account for a velocity-dependent covering fraction, and it is a poor representation for absorption associated with a dynamical outflow. Analysis techniques that use a single covering fraction value for each absorption component suffer from similar limitations.

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