A CONSTANT TOTAL PRESSURE MODEL FOR THE WARM ABSORBER IN NGC 3783

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ABSTRACT

Many AGN exhibit X-ray absorption features caused by the presence of highly ionized gas located on the line-of-sight of the central continuum. Such a material is called "Warm Absorber" (WA) and displays zones of different density, temperature and ionization. Our approach to the study of the WA relies on the assumption of pressure equilibrium, resulting in the natural stratification of the medium, which allows us to explain the presence of lines from different ionization states in many AGN observed by *Chandra* and *XMM-Newton*. Among the best WA observations available are those of NGC 3783, which we have analyzed.

We have used the photoionization code TITAN, developed by our team, to calculate a grid of constant total pressure models dedicated to fit the WA in NGC 3783. Our study shows that the WA can be modelled in pressure equilibrium. Finally, this work provides a good example of the application of the TITAN code to the study of the WA in AGN, and opens perspectives for its use by the community, through a larger grid of constant total pressure models to be made available via XSPEC and/or via Virtual Observatory facilities.

Key words: active galactic nuclei: NGC 3783; warm absorber.

1. INTRODUCTION

Many Active Galactic Nuclei (AGN) exhibit important X-ray absorption features caused by the presence of highly ionized gas located on the line-of-sight of the central continuum; such a material is called "Warm Absorber" (hereafter WA).

The first observations of WA gas in AGN were reported by Halpern et al. (1984) in the *Einstein Observatory* spectrum of MR 2251−178, a quasar displaying a large absorption feature around 1 keV; this feature has been attributed to the O VII (739 eV) and O VIII (871 eV) photoelectric absorption edges (*e.g.* George et al. 1995) and is consistent with the presence of gas photoionized by the hard X-rays produced near the central engine of the active nucleus.

Early *ASCA* observations have revealed the presence of ionized soft X-ray absorption in $\sim 50\%$ of type 1 Seyferts; evidence for a WA was also found in type 2 Seyferts, Narrow Line Seyfert 1s, BAL QSOs and even some BL Lacs. With the advent of space X-ray observatories such as *XMM-Newton* and *Chandra*, carrying aboard high-resolution grating spectrographs, an important set of high quality data became available providing valuable information on the WA. Spectra of type 1 objects revealed the presence of tens of absorption lines, covering a wide range of ionization states, and blueshifted by a few hundreds to thousands $\mathrm{km\,s^{-1}}$ (an indication that the absorbing material is outflowing); in type 2 AGN, the data have shown the presence of emission lines.

Despite the undeniable improvements in our knowledge of the WA, some important issues remain a subject of debate, namely: *(i)* the location and geometry of the WA, *(ii)* the physical conditions of the absorbing/emitting gas, and *(iii)* the implications of the WA in the energetics of AGN. Trying to solve these questions requires not only high quality observations, as the ones provided by *XMM-Newton* and *Chandra*, but also an adequate treatement of the X-ray data through the use of reliable photoionization codes, calculating the full radiative transfer.

We have addressed the above mentioned points through the study of the Warm Absorber in NGC 3783, for which unmatching quality *Chandra* archive data are available; we have modelled the data using our photoionization code TITAN (*e.g.* Dumont et al. 2000; Collin et al. 2004), which supports the assumption of pressure equilibrium and allows for a multi-angle analysis of the spectra.

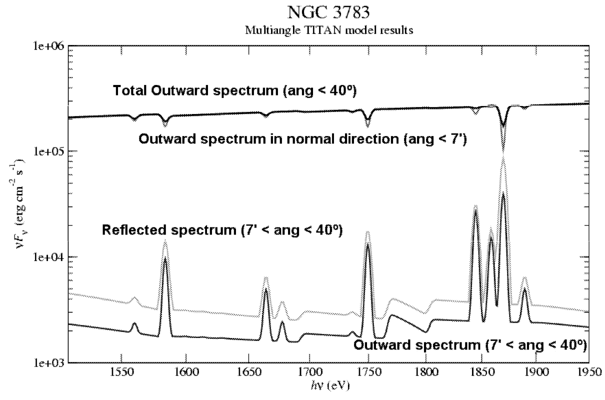

Figure 1. Absorption (outward spectrum inside an opening cone of 7′) and emission components (outward and reflected spectra in a cone comprised between 7′ and 40°). This figure illustrates how an absorption feature can be partially, or totally filled in by an underlying emission component, and stresses the importance of a separate analysis of the absorption and emission spectra.

2. THE WARM ABSORBER IN NGC 3783

NGC 3783 is a bright (V∼13.5), nearby (z=0.0097) Seyfert 1.5 galaxy observed in the Optical, UV and X-rays. The WA in this object has been discussed by several authors (*e.g.* Kaspi et al. 2001, 2002; Netzer et al. 2003; Krongold et al. 2003; Behar et al. 2003) based on *Chandra* data (56 ks and 900 ks spectra) and *XMM-Newton* observations (40 ks and 280 ks spectra). These studies seem to agree on the presence of a 2 (or more)-phase gas (a cold Low-Ionization Phase and a hot High-Ionization Phase) and on the absorbing and emitting plasma being manifestations of the same gas. Concerning the kinematics of the WA, two or more velocity systems have been identified in *Chandra* observations; they are compatible with those observed in UV spectra. A single velocity system ($v_{out} \sim$ 600–800 km s^{-1}) seems enough to describe *XMM-Newton* observations. There is no consensus in what concerns a possible correlation between the velocity shifts or the *FWHMs* with the ionization potentials of the ions.

Although the WA in NGC 3783 has been the object of many studies, these have assumed constant density (*e.g.* Netzer et al. 2003) or a dynamical state (Chelouche & Netzer 2005) for the modelling. In addition, they all require multiple zones of different density, temperature and ionization; these are invoked to explain the large span in ionization observed in the WA spectrum. Furthermore, when plotted on the S-curve of thermal equilibrium $log(T)$ *vs.* $log(\xi/T)$ (where T is the temperature of the medium and ξ is the ionization parameter[1]), these clouds lie on a vertical line of roughly the same gaseous pressure. However, a stratified medium can be obtained naturally if we assume the gas to be in pressure equilibrium.

[1]The ionization parameter ξ is defined as $L/n_{\rm H}R^2$, where L is the luminosity integrated over the total spectrum, $n_{\rm H}$ is the hydrogen density and R is the distance from the WA to the illuminating source.

Our approach to the study of the WA relies therefore on the assumption of constant total pressure, which allows us to explain the presence of lines from different ionization states, and accounts naturally for the other properties of a model composite of multiple constant density clouds.

3. DATA REDUCTION AND MODELLING

We have searched the *Chandra* archives for the HETG data used to build the 900 ks spectrum published by Kaspi et al. (2002), which is a combination of MEG and HEG observations. In this study, we have only considered HEG data. The retrieved spectra were treated in the standard way using the CIAO software (vs. 3.2.1) and corresponding threads. We have then used our photoionization code TITAN to model the observations and to constrain the physical conditions of the WA gas in NGC 3783.

TITAN is well suited for the study of optically thick and thin media; it computes the gas structure in thermal and ionization equilibrium, both locally and globally; it can work under constant density, constant gaseous pressure or constant total pressure. Our atomic data includes ∼1000 lines from ions and atoms of H, He, C, N, O, Ne, Mg, Si, S and Fe; more lines should be added soon.

The photoionization code TITAN accounts for Compton heating and cooling corresponding to photons with energies inferior to 25 keV; when coupled with the Monte-Carlo code NOAR, it can also account for the Compton heating and cooling corresponding to photons with energies larger than 25 keV.

Another important aspect of TITAN, is its multi-angle treatment of the transfer allowing, in particular, for the separate study of the emission and absorption components. As an example, Fig. 1 displays the calculated outward (absorption and emission), reflected (emission only) and total spectra (corresponding to the sum of the absorption and emission components) for NGC 3783, in the conditions of our best model described further down. This figure shows the importance of a separate analysis of the absorption and emission components, and illustrates how an absorption feature can be partially, or totally filled in by an underlying emission component; one can also see that the emission-line spectra corresponding to the reflected and outward flux are not similar, displaying different line-ratios.

We have calculated a grid of 16 constant total pressure models dedicated to fit the WA in NGC 3783; the 16 models cover the combinations between 4 possible values of the ionization parameter ξ ($2000 < \xi < 3500$ erg cm s^{-1}) and of the total column density ($3\,10^{22} < N_{\rm H} < 6\,10^{22}$ cm^{-2}); the density at the face of the cloud ($n_{\rm H}$) was set to 10^5 cm^{-3} and the turbulent velociy to 150 km s^{-1}. Our study shows that the WA can be modelled in pressure equilibrium conditions, providing a best model with $\xi = 2500$ and $N_{\rm H} = 4\,10^{22}$.

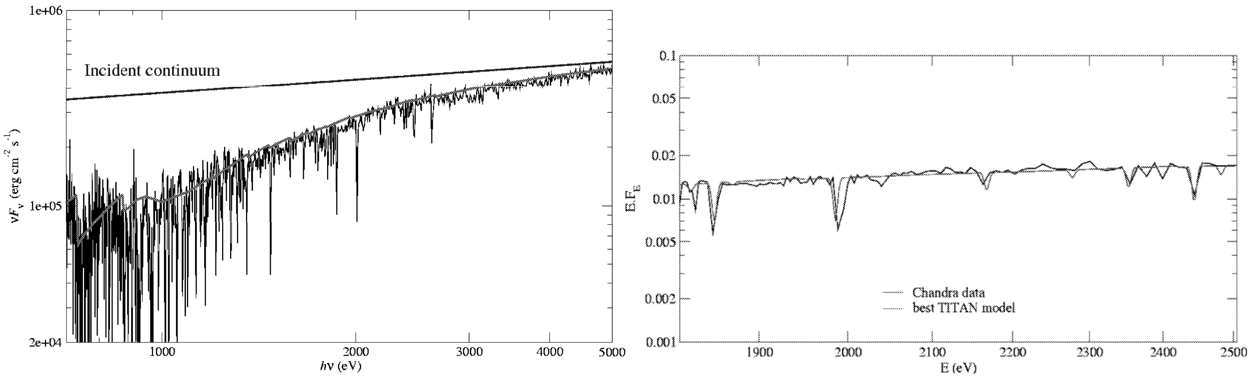

Figure 2. NGC 3783 observations and TITAN model. Left panel: incident and emergent continua plotted over the observations. Righ panel: zoom on the observed and modelled spectra. The "unfitted" features correspond to Al lines (not present in the atomic data).

This model gives a good fit to the observed data (Fig. 2), both for the continuum (following its overall shape up to 10000 eV and reproducing the O VII and O VIII edges) and the lines (both from high and low ionization); these are blueshifted by $\sim 810\,\mathrm{km\,s^{-1}}$. The observed and modelled spectra will be presented in detail in a forthcoming paper (Gonçalves et al., in preparation).

4. CONSTANT DENSITY VERSUS CONSTANT TOTAL PRESSURE MODELS

Our results can be compared to those of Netzer et al. (2003), who found three constant density clouds: a "low-ionization" cloud ($\xi = 68$ and $N_{\rm H} = 8\,10^{21}$), a "medium-ionization" cloud ($\xi = 1071$, $N_{\rm H} = 1\,10^{22}$), and a "high-ionization" one ($\xi = 4265$, $N_{\rm H} = 2\,10^{22}$).

We have studied the behaviour of the temperature, pressure and density for both constant density and constant total pressure models. In Fig. 3 we give the temperature for the three constant density clouds in Netzer et al. (2003) and for our WA in pressure equilibrium. As an example, Fig. 4 shows the Oxygen ionization fractions for both cases. Our results show that the WA in NGC 3783 can be modelled by a single medium in pressure equilibrium, instead of a composite medium of multiple constant density clouds.

As a good illustration of the agreement between an unique constant total pressure model and the composition of several constant density models, one can compare the values of the "observed" ionic column densities (*i.e.* those which have been determined through a curve of growth analysis in Netzer et al. 2003), with those deduced from our best model, and from the composite model of Netzer et al. (2003). Fig. 5 displays the computed column densities *vs.* the observed ones for both cases. One can see that both models give very similar results, even if these do not agree perfectly with the observations.

Based on our best model results and on the object's luminosity and black hole mass, we were able to make some preliminary estimates of physical quantities related to the WA. Assuming $n_{\rm H} = 10^5\ \mathrm{cm^{-3}}$, the size of the WA medium achieves $\Delta R \sim 2\,10^{17}$ cm. We should note here that constant pressure models vary only proportionally with $n_{\rm H}$ varying in the range 10^5 to 10^{12}; however, assuming a higher value of $n_{\rm H}$ at the face of the cloud would imply a smaller size for the WA medium. For a WA size of $\sim 2\,10^{17}$ cm, and in order to keep the amount of outflowing material within reasonable limits ($\dot{M}_{\rm out}/\dot{M}_{\rm Edd} < 1$), the WA should be located closer than $\sim 2\,10^{18}$ cm (*i.e.* before the Narrow Line Region). This is in agreement with the values put forward by Netzer et al. (2003) and Krongold et al. (2003).

Based on the absence of variability on timescales of 1 to 4 days, Netzer et al. (2003) conclude that the aborbers in NGC 3783 are located far from the central source, and that their densities are small, at most of the order of $n_{\rm H} = 10^5\ \mathrm{cm^{-3}}$. Accordingly, the thickness of the WA should be large ($\Delta R \geq 2\,10^{17}$ cm). The dynamical time scale of the WA is of the order of at least $\Delta R/c_{\rm s}$, where $c_{\rm s}$ is the sound velocity. If the gas pressure dominates, $c_{\rm s}$ is very roughly (since it varies by almost one order of magnitude) of the order of $10^7\ \mathrm{cm\,s^{-1}}$, which means that the dynamical timescale in this object is of the order of 10^3 years.

If radiation pressure dominates (as it is the case in our model), $c_{\rm s}$ is larger, and the dynamical timescale is reduced in proportion. Nevertheless, it would stay far much longer than the timescale for the flux variations. It can thus be objected that the medium cannot reach a state where it is in pressure equilibrium with the illuminating source; this is actually not true at the zeroth order. Indeed, the medium would then adopt a "quasi-pressure equilibrium" corresponding to a flux averaged over a long time, and the flux variations would induce rapid, but relatively small changes of the temperature and of the ionization equilibrium, keeping the same density structure, and the spectrum would not be strongly modified (work in preparation).

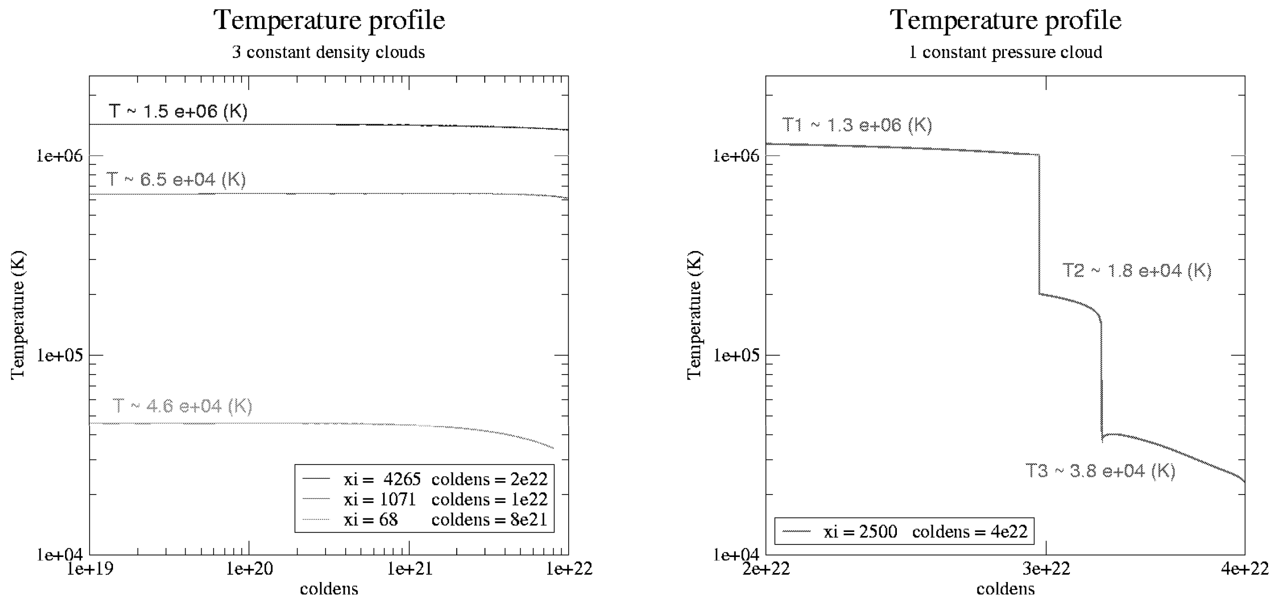

Figure 3. Left-hand panel: Temperature profiles calculated for the three constant density WA clouds described in Netzer et al. (2003). The top curve corresponds to the "high-ionization" cloud, the intermediate curve to the "medium-ionization" cloud, and the bottom curve, to the "low-ionization" cloud. Right-hand panel: Temperature profile resulting from our modelling of the WA as a single medium in total pressure equilibrium; notice that in this case, the temperature discontinuities arise naturally.

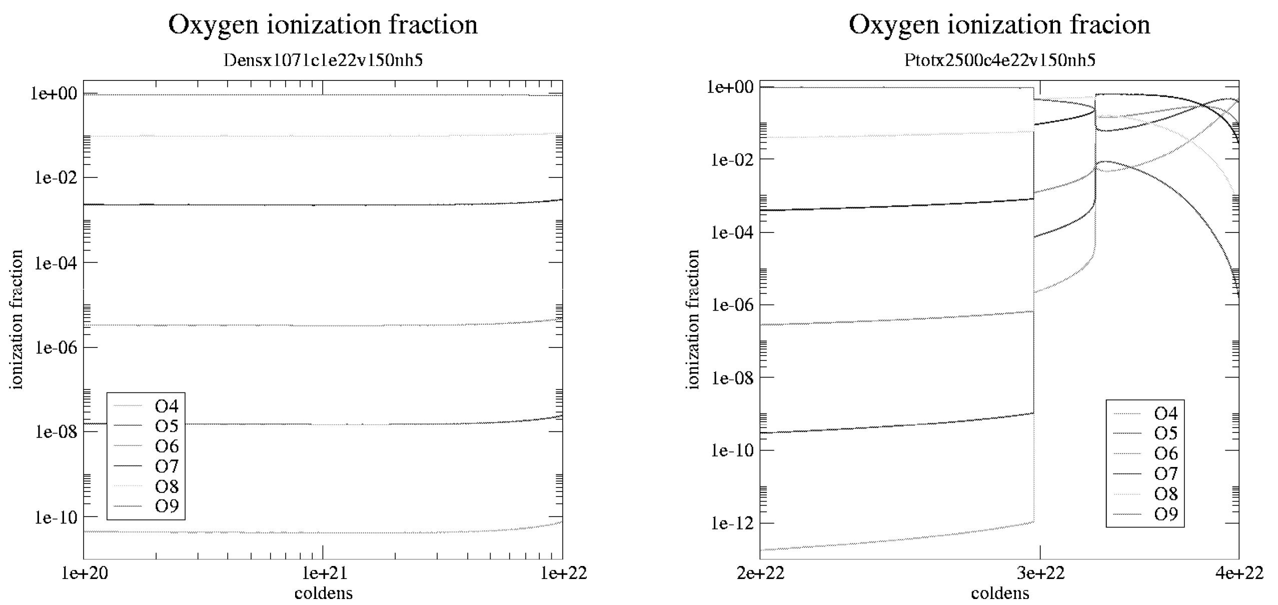

Figure 4. Ionization fraction of the oxygen ions ("Oi" stands for Oxygen ionized "i-1" times); from top to bottom, the curves correspond to the ions O IX, O VIII, O VII, O VI, O V *and* O IV. *Left-hand panel: ionization fractions for the "medium-ionization" constant density cloud described in Netzer et al. (2003); we note that in this case, only 2 species (*O VII *and* O VIII*) contribute significantly to the final spectrum. Right-hand panel: ionization fractions resulting from our modelling of the WA as a single medium in total pressure equilibrium; we note that in this case all ionic species contribute to some extent to the final spectrum, justifying the wide range in ionization species observed in this object.*

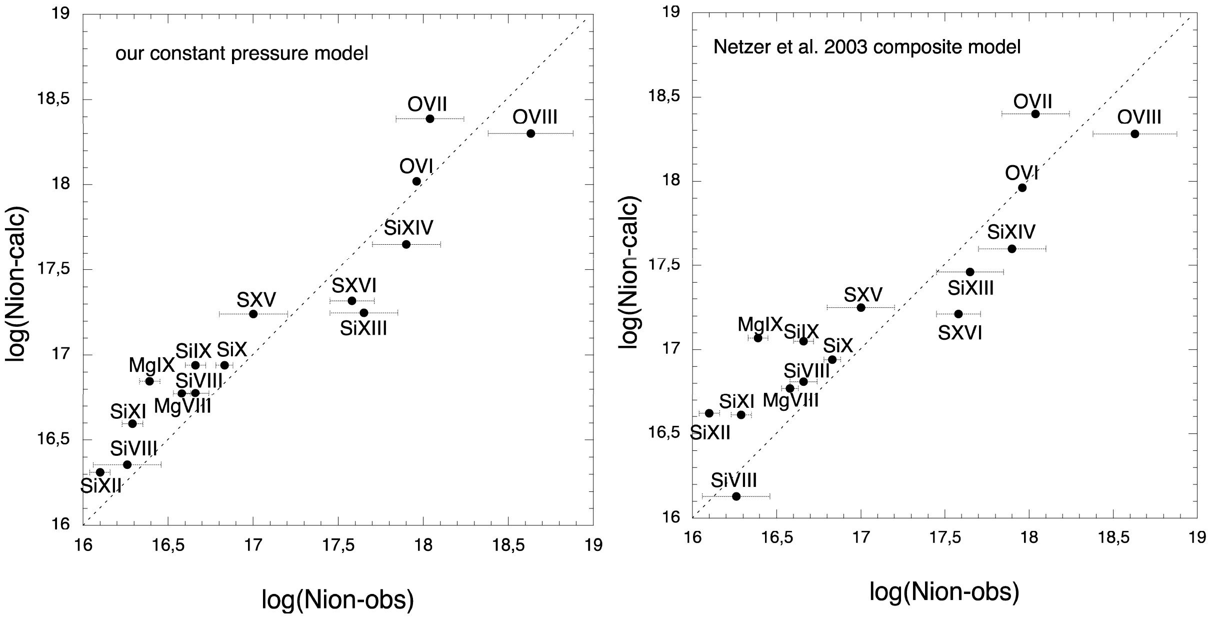

Figure 5. Ionic column densities for the Netzer et al. (2003) composite constant density model (right panel), and for our constant total pressure model (left panel), vs. the "observed" column densities determined through a curve of growth analysis (Netzer et al. 2003). The observed O VI *column density value corresponds to a lower limit, only; it was therefore replaced by the Netzer et al. (2003) computed value, which explains the absence of an error bar for this ion. The dotted line shows the diagonal on which the calculated ionic column densities equal the observations.*

Moreover, we observe that the three constant density components of the Netzer et al. (2003) model are located on the thermal stability S-curve at positions corresponding to roughly the same gas pressure (for the same radiative pressure). Therefore, even in the composite constant density model of Netzer et al. (2003), there should also exist a mechanism able to maintain a state of pressure equilibrium (different from our own state, as it does not involve a modification of the ionizing continuum accross the slabs).

Finally, one should take into account that the location of the WA absorber in NGC 3783 is still a controversial matter. A careful analysis of the emission lines and/or P Cygni-like features observed in the spectrum of NGC 3783 (probably due to both outward and reflection components) could help constraining the covering factor in this WA, and provide important information on its geometry and location.

As an example of the studies one can carry on such high-resolution spectra, Fig. 6 shows the absorption/emission blending for the O VIII λ18.969 line, as described in Krongold et al. (2003); superposed to the data, we show our own modelling of the P Cyg-like profile (thick line), obtained with a combination of absorption and emission spectra calculated with a turbulent velocity of 200 km s^{-1}; we note here that a lower turbulent velocity (*e.g.* 150 km s^{-1}) does not provide a satisfactory fit. In this tentative modelling of the O VIII line, the absorption component has a resolution of 300 and is represented at rest wavelength, while the emission component has a resolution of 600 and is resdshifted with respect to the absorption. Such a preliminary result suggests that the WA medium is rather complex; it could be that the absorption and emission gas do not originate on the same region, or even that the reflection flux could contribute to some ex-

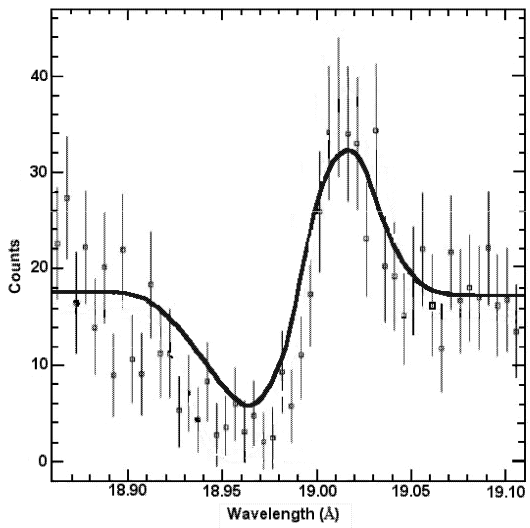

Figure 6. Absorption/emission blending for the O VIII λ18.969 *line, as described in Krongold et al. (2003); superposed to the data, we show our own modelling of the P Cyg-like profile (thick line), obtained with a combination of absorption and emission spectra calculated with a turbulent velocity of 200 km s^{-1}.*

tent to the final (total) observed spectrum. These subjects are still under study and will be discussed in more detail in a forthcoming paper (Gonçalves et al., in preparation).

In addition, this preliminary work shows the importance of the turbulent velocity in the description of the observed spectral features. Our grid of models was calculated for a turbulent velocity of $150\,\mathrm{km\,s^{-1}}$; a new grid is now being calculated for a higher value of the turbulent velocity, for comparison.

5. CONCLUSIONS AND FUTURE WORK

Our work demonstrates that the TITAN code is well adapted to the study of the WA in Active Galactic Nuclei. In particular, its multi-angle treatement of the transfer will be useful in the study of the emission-line spectrum of NGC 3783, and hopefully provide important information on the geometry and location of the Warm Absorber in this object.

We have shown that the WA in NGC 3783 can be modelled by a single medium in total pressure equilibrium; this is probably the case for all WA presently described by multiple zones of constant density. Such a pressure equilibrium can be reached if we assume the flux to be averaged over a long time.

In the case of NGC 3783, our grid of models has provided a best result corresponding to $\xi = 2500\,\mathrm{erg\,cm\,s^{-1}}$ and $N_{\mathrm{H}} = 4\,10^{22}\ \mathrm{cm^{-2}}$. This model fits the observations well, both for the continuum and the lines; these are blueshifted by $\sim 810\ \mathrm{km\,s^{-1}}$. Our grid of constant total pressure models, dedicated to the study of NGC 3783, is now ready to be inserted into XSPEC; this analysis will provide a more quantitative appreciation of our fit to the *Chandra* data, and will be discussed in more detail in a forthcoming paper (Gonçalves et al., in preparation).

In addition, our work opens perspectives for the future use of the TITAN code by the community, through a larger grid of constant total pressure models to be made available via XSPEC and/or via Virtual Observatory facilities.

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