A SINGLE MEDIUM MODEL FOR THE WARM ABSORBER IN NGC 3783

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The "Warm Absorber" (WA) observed in Active Galactic Nuclei (AGN) displays zones of different density, temperature, and ionization. Such a medium is generally described by multiple regions modelled in constant density. Our approach to the study of the WA relies on the assumption of pressure equilibrium, which results in the natural stratification of the medium and allows 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. Models in pressure equilibrium present temperature discontinuities which, however difficult to tackle, can be adressed with the photoionization code TITAN, developed by our team. We have used this code 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 by a single medium in total pressure equilibrium; this could be the case for other warm absorbers presently modelled with multiple regions in constant density. In addition to describing the X-ray spectra, our models provide ionic column densitites for the lower ionization species that give rise to absorption lines in the UV. This information could be explored in future work, by extending our WA studies to the UV range.

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 Seyferts 1s; evidence for a WA was also found in Seyferts 2s, 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* 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 the AGN. Trying to solve these questions requires not only high quality observations, as the ones provided by the new generation of satellites, 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 WA in NGC 3783, described in Section 2. We have modelled the data using our photoionization code TITAN, which supports the assumption of pressure equilibrium and allows for a multi-angle analysis of the emergent spectra; a more complete description of the code can be found in Section 3. In Section 4 we briefly describe our models. Sections 5 and 6 summarize our results and conclusions.

2. The Warm Absorber in NGC 3783

NGC 3783 is a bright ($V \sim 13.5$), nearby ($z = 0.0097$) Seyfert 1.5 galaxy extensively observed in the Optical, UV and X-rays. It disposes of unrivaled quality *Chandra* /HETGS archive data (Kaspi *et al.* 2002).

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). In what concerns the kinematics of the WA, two or more velocity systems have been identified in *Chandra* observations; they are compatible with those observed in the UV spectra. A single velocity system ($v_{out} \sim 600$–$800\,\mathrm{km\,s^{-1}}$) seems enough to describe *XMM-Newton* observations, which have lower spectral resolution. 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, suggesting that a single medium in pressure equilibrium could account for the WA in this object.

Or, a stratified medium can be obtained naturally if we assume the gas to be in pressure equilibrium (e.g. Krolik & Kriss 2001; Różańska *et al.* 2006). However, considering the gas pressure only is not enough in some cases. We know that for relatively thin slabs, the radiation and gas pressure remain constant, the temperature does not vary much within the slab, and constant pressure models can be approximated by a constant density model. For thicker media, however, the ratio between the gas and the radiation pressure varies across the slab, inducing variations in the density and the temperature. In such cases, it is important to take the total (gas+radiation) pressure into account.

Our approach to the study of the WA in NGC 3783 relies therefore on the assumption of constant total pressure; we will see that such an assumption allows 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 regions.

3. The photoionization code TITAN

Although extremely useful in different astronomical contexts (e.g. Gonçalves & Soria 2006; Gonçalves *et al.* 2006), models in pressure equilibrium are seldom applied to the highly ionized gas in the vicinity of strong X-ray sources. This is mainly due to the lack of such a computational option in the principal codes available to the community, as well as to the fact such models require very sensitive and time-consuming computations. With the advent of present (e.g., *Chandra*, *XMM-Newton*, *Suzaku*, etc.) and future spatial X-ray missions (for instance, *Simbol-X*, *Con-X*), equiped with grating spectrographs and providing high-quality data, it is crucial to correctly model the line spectrum of X-ray emitting/absorbing media by using codes which do not rely on approximate formalisms (e.g. the "escape probability approximation"), but rather compute the exact transfer for both the continuum and the lines. This is the case for the photoionization code TITAN, developed by our team (Dumont *et al.* 2000, 2002, 2003; Collin *et al.* 2004).

The TITAN code is well suited for the study

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

of both optically thick (Thomson optical depth up to several tens) and moderately thin media (Thomson thickness of 0.001 to 0.1), characteristic of the WA in Seyfert 1s or of the X-ray emitting medium in Seyfert 2s. The code treats all relevant physical processes from each level (e.g., photoionization, radiative and dielectronic recombination, ionization by high energy photons, fluorescence and Auger processes, collisional ionization, radiative and collisional excitation/de-excitation, etc.) and all induced processes. It solves the ionization equilibrium of all the ion species of each element (our atomic data include $\sim 10^3$ lines from ions and atoms of H, He, C, N, O, Ne, Mg, Si, S, and Fe), the thermal equilibrium, the statistical equilibrium of all the levels of each ion, and the transfer of the lines and of the continuum. It gives as output the ionization, density, and temperature structures, as well as the reflected and outward spectra. The energy balance is ensured locally with a precision of 0.01%, and globally with a precision of 1%.

Its advantage over other photoionization codes, such as CLOUDY (Ferland *et al.* 1998) or XSTAR (Kallman & Bautista 2001), relies in the fact that it treats the transfer of both the lines and the continuum using the Accelerated Lambda Iteration (ALI) method, which very precisely computes line and continuum fluxes. In addition, TITAN offers the possibility of treating the ionized gas in total (gas+radiation) pressure equilibrium, thus offering a more complete choice of models for the description of the highly ionized gas in the vicinity of a strong X-ray source. Models in pressure equilibrium present temperature discontinuities which, however difficult to tackle, can be adressed with our code (Gonçalves *et al.* in preparation).

4. Data reduction and modelling

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

In our modelling, we assume a primary source of radiation characterized by a certain Spectral Energy Distribution (SED). The medium surrounding this primary source is radiatively heated and photoionized. If the ionized medium is sufficiently far from the ionizing source, we can treat it in a 1-D plane-parallel geometry, as a slab of gas illuminated from one side by a radiation field concentrated in a very small, pencil-like, shape centered on the normal direction. The incident SED used, given in Kaspi *et al.* (2001), covers the 0.2 eV–400 keV range.

We have computed a grid of 16 constant total pressure models to fit the WA in NGC 3783, covering the combinations of 4 possible values of the ionization parameter ($2000 < \xi < 3500$) and of the total column density ($3\,10^{22} < N_{\rm H} < 6\,10^{22}$). The $n_{\rm H}$ at the illuminated side of the medium was set to 10^5 cm^{-3} (Netzer *et al.* 2003) and the the turbulent velocity to 150 km s^{-1} (Kaspi *et al.* 2000). The models were computed using two different sets of abundances: the cosmic abundances of Allen (1973), and the ones used by Netzer *et al.* (2003), for the purposes of comparison.

We note here that the turbulent velocity deduced from the observations and used in our modelling is highly supersonic compared to the thermal velocity in the absorbing medium. It is possible to address this situation either by taking into account the strong dissipation occuring through shock waves in the supersonic medium (this leads to a higher temperature than in a purely photoionized case), or by assuming a photoionized, inhomogeneous medium with several clumps lying in the line-of-sight. These gas clumps have an average relative velocity, that we identify as the turbulent velocity. We thus assume the WA in NGC 3783 to consist of such gas blobs embedded in a surrounding, hotter medium. The clumpy WA medium is assumed to be in total pressure equilibrium. We include the gas and the radiation pressure in the total pressure, but not the turbulent pressure resulting from taking a non-zero turbulent velocity, since it is a quantity exterior to the clumps. One should, however, take the effects of the turbulent velocity into account when computing the radiative transfer; this has been done for all our models.

5. Results

Our study shows that the WA in NGC 3738 can be modelled in pressure equilibrium conditions, providing a best model with $\xi = 2500$, $N_{\rm H} = 4\,10^{22}$, and cosmic abundances. This model

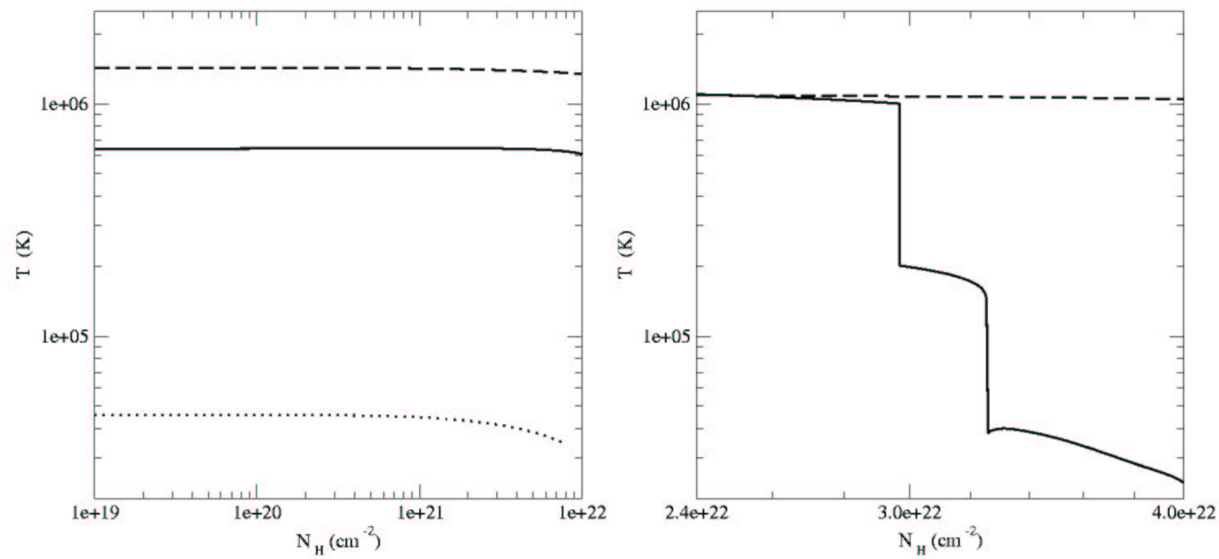

Figure 1. Left-hand panel: Temperature profiles computed with TITAN for the three constant density WA regions described in Netzer et al. (2003). The dashed line corresponds to the "high-ionization" zone, the solid line to the "medium-ionization" zone, and the dotted line to the "low-ionization" zone. Right-hand panel: The solid line represents the temperature profile obtained for our WA model using a single medium in total pressure equilibrium; in this case, the temperature discontinuities arise naturally. The dashed line corresponds to a single-zone WA with the same parameters, only modelled in constant density. The models in this figure were computed witht the same code, abundances, turbulent velocity and $n_{\rm H}$ value.

gives a good fit to the observed data, 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 ~ 810 km s^{-1}.

Our results can be compared to those of Netzer *et al.* (2003), who provide a detailed modelling of the WA in NGC 3783; these authors found three constant density components with different ξ and $N_{\rm H}$ values: a "low-ionization" region with $\xi = 68$ and $N_{\rm H} = 8\,10^{21}$, a "medium-ionization" region with $\xi = 1071$ and $N_{\rm H} = 1\,10^{22}$, and finally a "high-ionization" region with $\xi = 4265$ and $N_{\rm H} = 2\,10^{22}$. We have studied the behaviour of the temperature, pressure, and density for both the constant density and constant total pressure models. In Fig. 1 we compare the temperature profiles computed for the three constant density WA regions described by Netzer *et al.* and for our WA modelling based on a single medium in total pressure equilibrium.

For all the models in our grid, irradiation by the incident SED resulted in the formation of a hot surface zone, with an almost constant temperature, followed by a rapid drop by one order of magnitude at a certain depth, and a second temperature drop deeper in the slab. The right-hand panel shows the temperature profiles for a constant density and a constant total pressure model, computed assuming the same parameters. We observe that, in the case of a constant density model, the temperature remains more or less constant along the medium. Thus, if a composite (i.e. multi-component) constant density model is assumed, as in Netzer *et al.*, a relatively flat temperature profile is found for each component, with a different temperature value for each one. This behaviour is clearly visible in the left-hand panel, where we show the temperature profiles computed with TITAN for the three regions described in Netzer *et al*. On the contratry, when a single medium in constant total pressure is assumed,

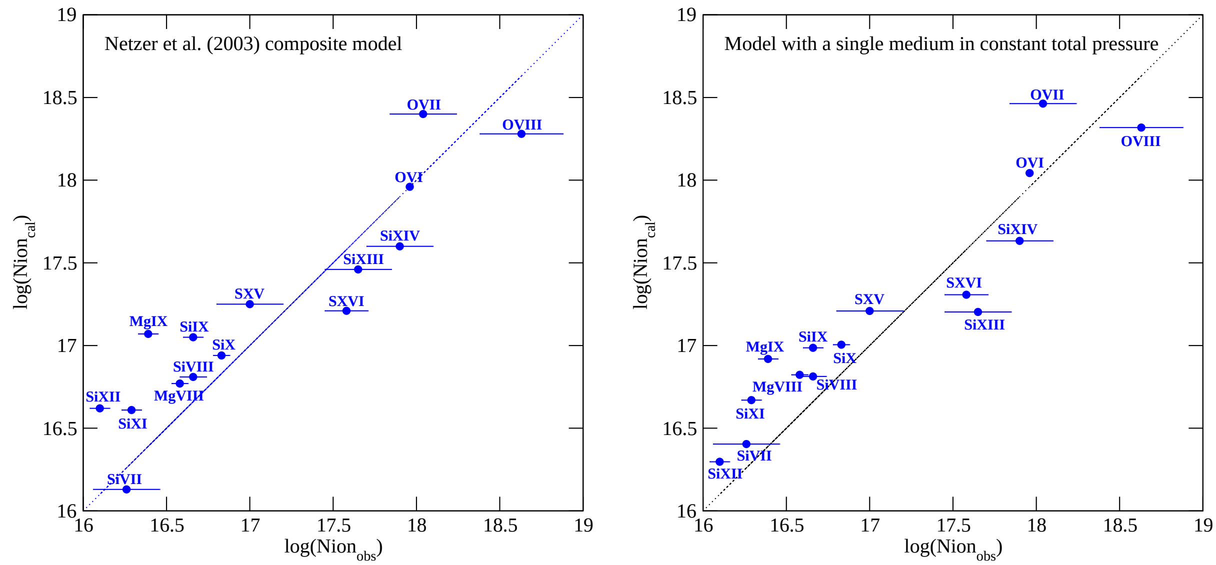

Figure 2. Computed ionic column densities (in cm^{-2}) for the Netzer *et al.* (2003) composite constant density model (left panel) and for our constant total pressure model (right panel) vs. the "observed" column densities determined through a curve of growth analysis. The observed O VI column density value corresponds to a lower limit, only. It was therefore replaced by the Netzer *et al.* computed value, which explains the absence of an error bar for this ion. The dotted line shows the diagonal on which the calculated values equal the observations.

the temperature drops arise naturally. Such variations in temperature are accompanied by ionization fronts, resulting in different ionization fractions for the three flat-temperature regions visible in the right-hand panel.

As an illustration of the good agreement between a single medium in constant total pressure and the three-zone model in constant density, one can compare the values of the computed ionic column densities deduced from our best model and from the composite model of Netzer *et al.* with the "observed" ones, determined through the curve of growth analysis in Netzer *et al.* (2003). Figure 2 shows that, within the uncertainties, both models should lead to similar absorption spectra; this comparison used the same incident SED and abundances. Although this figure only shows 15 ions (for comparison), our model provides ionic column densitites for all the other ions in the atomic data, which include the lower ionization species that give rise to absorption lines in the UV. It would thus be most useful to extend these studies by comparing our models to the available UV data on NGC 3783.

Based on our best model results, and on the object's bolometric luminosity ($L \sim 2\,10^{44}\,\mathrm{erg\,s^{-1}}$) and black hole mass ($M_{\rm BH} \sim 3\,10^7$ solar masses) (Peterson *et al.* 2004), we have calculated some quantities related to the WA. Assuming $n_{\rm H} = 10^5\,\mathrm{cm^{-3}}$ at the illuminated side of the slab, the size of the WA medium is $\geq 4\,10^{17}$ 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 $\sim 4\,10^{17}$ cm, and in order to to keep $\dot{M}_{\rm out}/\dot{M}_{\rm Edd} \leq 1$ (where $\dot{M}_{\rm out}$ and $\dot{M}_{\rm Edd}$ are the outflow and Eddington mass accretion rates), the WA should be located closer than $\sim 10^{18}$ 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). However, one should keep in mind that the location of the WA absorber in NGC 3783, and in other objects, 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 could help constraining the covering factor in this WA, and provide important information on its geometry and location.

6. Conclusions

1. 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 other warm absorbers presently described by multiple zones of constant density.

2. Our grid of models has provided a best result for $\xi = 2500$ erg cm s^{-1}, $N_{\rm H} = 4\,10^{22}$ cm^{-2}, and cosmic abundances. This model fits the observations well, both for the continuum and the lines.

3. Our work provides ionic column densities and equivalent widths for lower ionization species, observed in the UV range. This information could be explored in future work, by extending our WA studies to the UV range.

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