What Shapes the Absorption Measure Distribution in AGN Outflows?

T. P. Adhikari1,2, A. Różańska1, K. Hryniewicz1, B. Czerny3, and E. Behar4
1 Nicolaus Copernicus Astronomical Centre, Polish Academy of Sciences, Bartycka 18, 00-716, Warsaw, Poland; tek@camk.edu.pl
2 Inter-University Centre for Astronomy, Astrophysics (IUCAA), Pune 411007, India
3 Center for Theoretical Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, Warsaw, Poland
Department of Physics, Technion, Haifa 32000, Israel

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Abstract

The absorption measure distribution (AMD) in the X-ray outflows of Seyfert active galactic nuclei describes the distribution of absorbing column density as a function of ionization parameter. Up to now, the AMD has been measured only for seven objects with high-resolution X-ray data that contain absorption lines from ionized heavy elements. Even though the number of measured AMDs is not large, they display a universal broad shape containing a prominent dip, for which the absorbing column drops by around two orders of magnitude. In this paper, we test a range of photoionization models against the overall shape of the AMD as observed in Seyferts. In particular, we demonstrate that the shape of the AMD depends both on the spectral energy distribution (SED) of radiation that enters the outflow, and the density of the warm absorber (WA). The model that best reproduces the observed shape of the AMD is one wherein the gas density of the WA is of the order of $10^{12}$ cm$^{-3}$, irradiated by an SED whose optical/UV luminosity is 100 times higher than the X-ray luminosity. When the cloud density is higher than $\sim 10^{11}$ cm$^{-3}$, free–free heating dominates the entire absorber, and only one instability zone occurs, in agreement with observations.

Key words: galaxies: active – methods: numerical – quasars: absorption lines – radiative transfer

1. Introduction

The heavy element content in the intergalactic medium is constantly enriched by warm/hot outflows from active galactic nuclei (AGNs). X-ray spectral studies of those objects led to the detection of many blueshifted narrow absorption lines from highly ionized elements, providing a great opportunity to study the warm absorber (WA) in the vicinity of a supermassive black hole (SMBH) (Collinge et al. 2001; Kaspi et al. 2001; Kastra et al. 2002; Behar et al. 2003; Blustin et al. 2003; Krongold et al. 2003; Netzer et al. 2003; Steenbrugge et al. 2003a, 2005; Yaqoob et al. 2003; Różańska et al. 2004; Turner et al. 2004; Costantini et al. 2007; Winter & Mushotzky 2010; Tombesi et al. 2013; Laha et al. 2014, 2016; Mao et al. 2018; Silva et al. 2018, and other references therein).

The observed absorption lines typically indicate ionic column densities of the order of $10^{15}$–$10^{18}$ cm$^{-2}$ in the WA. For the given ionic column densities, the photoionization calculations done through thin constant-density slabs of matter allow the derivation of equivalent hydrogen column densities taking into account appropriate values of the ionization parameter. Various ions indicate a distribution of equivalent hydrogen column densities typically in the range $10^{18}$–$23$ cm$^{-2}$. These columns correspond to the continuous change of the ionization parameter $\xi$, which spans a range of a few decades when determined from the data of individual source (Steenbrugge et al. 2005; Costantini et al. 2007).

Holczer et al. (2007) proposed to describe the ionization structure of the wind by determining the absorption measure distribution (AMD), which describes how the equivalent hydrogen column density of the ionizing material behaves with the change of the ionization parameter along the line of sight. Since then, several attempts have been made to derive the continuous ionization structure of the WAs in several AGNs (Holczer et al. 2007; Behar 2009; Dettmers et al. 2011) utilizing high-resolution X-ray spectra. Measurement of the AMD strongly depends on the number of observed absorption lines. The more lines observed, the wider the range over which the ionization parameter is determined. For each line, the equivalent width has to be determined precisely; this can be properly done only using high-energy resolution detectors such as the gratings aboard the Chandra X-ray Observatory and XMM-Newton (Steenbrugge et al. 2003b; Costantini et al. 2007). Furthermore, the AMD error bars are mostly obtained from a Monte Carlo fitting method (see Holczer et al. 2007 for a detailed method description), and depend only slightly on the assumed abundances in the photoionization calculations (Holczer & Behar 2012).

Holczer et al. (2007) used Chandra observations of the WA in IRAS 13349+2438 to demonstrate that its AMD displays a deep minimum in column density, where it decreases by 2–3 orders of magnitude, and is consistent with negligible gas absorption for values of log $\xi$ between $\sim 0.8$ and $1.7$ (see Equation (1) below for a definition). Such deep minima are also present in the AMDs of other objects: NGC 3783, NGC 5548, MCG–6–30–15, NGC 3516, and NGC 7469 (Behar 2009). The overall measured normalization, defined as the average value of the AMD outside the dip, for these six sources is of the order of $\sim 4 \times 10^{31}$ cm$^{-2}$. However, the case of Mrk 509 differs: Dettmers et al. (2011) obtained two prominent dips around log $\xi$ $\sim 2$–3 and 3–4, with slightly lower normalization.

To reproduce the observed broad AMD theoretically, we consider a continuous ionization structure across the WA, so that photoionization computations return a broad range of ionization states. Each model for the WA contains a single gas cloud under constant total pressure (CTP; the sum of gas pressure and radiation pressure is a constant). At each column density depth, we can examine the temperature and ionization structure determined by all relevant heating/cooling processes. In such a cloud, parameters such as the ionizing spectral energy distribution (SED), ionization parameter, and gas density are defined only at the cloud surface. All of them change physically with cloud depth due to gas suppression by radiation pressure. This continuous ionization structure for the WA under CTP...
was presented by Różańska et al. (2006), and Gonçalves et al. (2007). Later, Stern et al. (2014) introduced the concept of deriving the AMD for a continuous ionization structure based on the assumption of a radiation pressure confinement (RPC) of the WA material. Using the CLOUDY\(^5\) photoionization code, Stern et al. were successful in reproducing the observed normalization and slope of the AMD for the six objects mentioned above. However, they were not able to quantitatively reproduce the deep minimum of the AMD. The difference between the RPC and CTP modes is that in the case of RPC, treated by the CLOUDY code, it is assumed that radiation pressure diminishes exponentially with optical depth (Equation (6) in Stern et al., 2014), while in the case of CTP, treated by the TITAN code the radiation pressure is self-consistently computed from the true intensity field (Dumont et al. 2003).

Adhikari et al. (2015, hereafter AD15) demonstrated that the two dips observed in the AMD of Mrk 509 can be successfully reproduced by assuming a single WA model under CTP using the TITAN photoionization code (Dumont et al. 2000). For the first time, AD15 confirmed that such deep minima in AMD are evidence of a thermal instability for a specific ionization and temperature regime. However, the observed normalization of AMD for Mrk 509 as obtained by Dettmers et al. (2011) is lower by a factor of ~30 than that obtained from the TITAN model of AD15 (see the lower panel of Figure 4.4 in AD15). (Goosmann et al. 2016) performed exactly the same photoionization computations with the TITAN code to explain the constant-pressure WA in NGC 3783, and they achieved the discontinuity in the AMD, but did not continue their computations in the thermally unstable region.

In order to understand what shapes the AMD in AGN outflows, in this paper we present a systematic study of WAs under CTP, and focus on the importance of the SED shape and the local density at the cloud’s irradiated face in shaping the AMD.

We employ the TITAN numerical code to simulate the photoionization process by computing the thermal and ionization structure of the absorbing gas subjected to the incident radiation field of the AGN. The resulting models, obtained for a large grid of parameter space, display thermal and ionization properties of absorbing gas which change continuously between different gas layers.

We had previously found that the AMD normalization drops by an order of magnitude when the WA gas is illuminated by an SED whose optical/UV flux is higher by two orders of magnitude than the X-ray flux (Adhikari et al. 2018b). Here, we continue this modeling work, and find that the overall SED shape influences the number dips present in the AMD.

Knowing how the SED influences the AMD normalization and the number of dips, we then investigate the dependence of AMD models on the density of the absorbing gas, and find that a high gas density, of the order of \(10^{12} \text{ cm}^{-3}\), and an ionization parameter of the order of \(10^3 \text{ erg cm}^{-1} \text{s}^{-1}\), provide the best representation of the observed shape of the AMD obtained by Behar (2009). This result provides additional support that the outflow observed in X-rays is very dense, and is in agreement with recent indications that the density of the broad-line region (BLR) is equivalently high (Hrynewicz et al. 2012; Adhikari et al. 2016, 2017, 2018a; Panda et al. 2018), suggesting that both the WA and BLR may originate from the upper, dense accretion disk atmospheres, even if the gas dynamics are not the same. Interestingly, the investigation of the photoionization properties of the BLR led to estimates of its optimal density being about \(10^{10} \text{ cm}^{-3}\) (Osterbrock & Ferland 2006).

A description of photoionization computations together with input parameters is presented in Section 2. The dependence of the AMD models on SED shape, ionization parameter, and gas density is discussed in Section 3, while Section 4 contains a comparison of our model with the observed AMD shape. Finally, a discussion and conclusions are presented in Sections 5 and 6, respectively.

2. Photoionization Models

We computed the photoionization models using the numerical code TITAN (Dumont et al. 2000; Różańska et al. 2004) under the assumption that an X-ray absorber in an AGN is in total pressure equilibrium, sustained by the CTP condition. As demonstrated in earlier works (Dumont et al. 2003; Różańska et al. 2006; AD15), TITAN uses the ALI (accelerated lambda iteration; Paletou & Auer 1995) method of radiative transfer computations and allows us to clearly resolve the thin layers of strong temperature and density gradients that develop in the photoionized gas cloud.

In this paper, we consider a CTP single gas cloud defined by the following parameters: number density \(n_{H,0}\) and ionization parameter \(\xi_0\) both assumed at the illuminated surface, and the total column density \(N_{H}^{\text{tot}}\) (see Section 3 of AD15 for a general description of parameters in TITAN photoionization computations). Due to illumination by the AGN radiation field from one side, such a cloud forms a highly stratified medium with strong gradients in density, temperature, and ionization state. The cloud stratification is calculated self-consistently by solving the ionization and thermal balance across it.

The ionization parameter strongly varies with depth through the cloud, and we calculate its value within a cloud as a function of the optical depth measured from the illuminated cloud using the expression

\[
\xi = 4 \pi c k T \frac{P_{\text{rad}}}{P_{\text{gas}}} = 4 \pi c \frac{P_{\text{rad}}}{n_H} \tag{1}
\]

where \(c\) is the velocity of light, and \(k\) is Boltzmann’s constant. In the above definition, the ionized radiation is integrated over the whole range of the ionizing continuum, as described below. This differs from the original definition, where ionized radiation is integrated over the hydrogen ionizing continuum from 1 to 1000 Ry (Krolik et al. 1981). Such a difference is always taken into account in this paper when introducing the value of the input ionization parameter.

The temperature \(T\), number density \(n_H\), radiation pressure \(P_{\text{rad}}\), and gas pressure \(P_{\text{gas}}\) are computed self-consistently by TITAN at each layer of the photoionized gas cloud. The values of the local density and gas pressure take into account all partial ionization states for the fractional abundances obtained from the ionization and thermal balance. The radiation pressure is self-consistently derived from the second moment of the radiation field after checking that radiation balance is sustained globally.

For each computed model, the AMD is derived by taking into account the stratification of the ionization parameter \(\xi\),

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\(^5\) See Ferland et al. (2017) for the latest information on the numerical code CLOUDY.
using the following relation:

\[
\text{AMD} = \frac{dN_H}{d(\log \xi)} = 2.303 \frac{\xi dN_H}{d\xi}. \tag{2}
\]

We compute a large grid of models for initial gas parameters defined at the cloud surface: \(\xi_0\) from \(10^2\) up to \(10^5\) erg cm s\(^{-1}\) with a logarithmic grid step equal to 1, and \(n_{H_0}\) from \(10^8\) up to \(10^{15}\) cm\(^{-3}\) with the same grid step. The total column density of the clouds \(N_{H_0}\) spans from \(10^{20}\) to \(10^{23.5}\) cm\(^{-2}\) with a logarithmic grid step equal to 0.5. The most interesting clouds are those with large total column densities, since they include all ionization fronts, and their temperature structure goes from high Compton temperature (~\(10^7\) K) down to the lowest value (~\(10^1\) K) on the non-illuminated side of the cloud. In particular, it means that the gas hosts a broad range in ionization degree.

In order to investigate what shapes the AMD in AGNs, we employed various types of AGN SEDs (Section 2.1) in our computations together with the above values of ionization parameter, the gas density on the cloud surface, and the total gas column density. Since our grid of models is already large—up to 800 cases—we did not explore the effect of metallicity here, fixing it at the solar value. Selected important results of our photoionization computations are presented in Section 3.

### 2.1. General SED Shapes

An important input parameter in photoionization simulations is the shape of the ionizing SED, which influences the thermal and ionization structure of the WA cloud. Studies of the stability curve for different shapes of the radiation field have revealed that the resulting curves are significantly different, and in particular very sensitive to the UV/soft X-ray part of the SED (Różańska et al. 2006, 2008; Chakravorty et al. 2009, 2012). If the ionizing continuum is sufficiently soft, i.e., dominated by the UV/soft X-ray band, the thermal and ionization states of the WA are sensitive to their density apart from the usual dependence on the ionization parameter (Różańska et al. 2008; Chakravorty et al. 2009).

To make systematic studies of the AMD, we consider a range of SED shapes, assuming that the overall spectrum originates from the AGN. This emission is represented by two major components that contribute to the broad AGN spectrum: a multi-blackbody disk spectrum and an X-ray power law with an exponential cut-off. The variation in SED shape is achieved by varying the dimensionless mass accretion rate relative to the Eddington rate \(\dot{m}\), and the power-law photon index \(\Gamma\). The mass of the SMBH is taken as \(M_{\text{BH}} = 10^8 M_\odot\), and the high energy cut-off \(E_{\text{cut}} = 100 \text{ keV}\) in all cases.

Since the incident radiation has already two free parameters, \(\dot{m}\) and \(\Gamma\), and considering the input parameters for the WA (\(\xi_0\), \(n_{H_0}\), \(N_{H_0}\)), the number of computed models is very large, and each model requires 24 hr CPU time. So, for clarity, we present here only those models that we found to be most crucial in shaping the AMD. In particular, we divide our models into two groups of SED which differ by the strengths of the blackbody disk emission and by the relative normalization of disk to X-ray power-law emission. The first group, named SED A (depicted in Figure 1), represents the case dominated by the big blue bump component, and is calculated for \(\dot{m} = 0.1\). The second group, named SED B (depicted in Figure 2), has blackbody disk emission 100 times weaker than for SED A, and is calculated for \(\dot{m} = 0.001\).

In the case of both groups of models A and B, the variation in the X-ray power-law slope is determined by taking 10 values of photon index \(\Gamma\) from 1.4 up to 3.2 with a grid step of 0.2. The observed values of \(\Gamma\) for typical AGNs are between 1.5 and 2.5 (Yuan et al. 2014 and references therein). Our range is slightly wider to emphasize the importance of hard X-ray photons on the high-ionization end of the AMD. While varying the X-ray photon index, the X-ray luminosity, resulting from integration of the power-law shape from 0.001 to 100 keV, is kept constant for a given value of \(\dot{m}\). This condition is achieved by varying the parameter \(\alpha_{OX}\) (Tananbaum et al. 1979). \(\alpha_{OX}\) describes the ratio of flux emitted at 2500 Å to that emitted in soft X-rays at 2 keV, and is defined by the relation

\[
\alpha_{OX} = -0.384 \log \left( \frac{F_{2\text{keV}}}{F_{2500\text{Å}}} \right). \tag{3}
\]

For group A SEDs, the blackbody disk component is always two orders of magnitude more luminous than the X-ray power law, while for group B SEDs, the luminosities of both components are equal. The total luminosity depends mostly on the disk accretion rate. The resulting two groups of

\[\text{Figure 1. SED A shapes dominated by the big blue bump (optical/UV) component. Cases with different X-ray photon indices are shown. The disk luminosity } L_{\text{disk}} \text{ is always 100 times higher than the X-ray luminosity } L_X.\]

\[\text{Figure 2. SED B shapes, where the disk luminosity } L_{\text{disk}} \text{ is comparable to the X-ray luminosity } L_X. \text{ Cases with different X-ray photon indices are shown.}\]
Table 1
Parameters Used for Computing the General SEDs

| SED | \( n \) | \( L_{\text{disk}} \times 10^{43} \) | \( L_X \times 10^{43} \) | \( \Gamma \) | \( \alpha_{OX} \) |
|-----|-----|----------------|----------------|-----|------|
| A   | 0.1 | 126            | 1.26           | 1.4–3.2 | −1.9 to −2.8 |
| B   | 0.001 | 126         | 1.26          | 1.4–3.2 | −1.3 to −2.1 |

Note. The mass accretion rate relative to Eddington \( n \), disk luminosity \( L_{\text{disk}} \) in erg s\(^{-1}\), the X-ray luminosity \( L_X \) in erg s\(^{-1}\), the photon index \( \Gamma \), and optical–X-ray index \( \alpha_{OX} \) are presented in columns 2, 3, 4, 5, and 6, respectively. The mass of the SMBH in all cases is taken as \( M_{\text{BH}} = 10^8 M_\odot \).

3. Initial Parameters and AMD Shape

In order to demonstrate most clearly how different SEDs affect the resulting AMD models, we fix the parameters at each cloud surface to be \( N_{\text{HI}} = 10^8 \text{ cm}^{-2} \) and \( \xi_0 = 1.36 \times 10^4 \text{ erg cm s}^{-1} \). For both groups A and B, only models with a broad ionization distribution are shown for various values of X-ray power-law photon index \( \Gamma \). Models with low values of initial total column density and extreme values of \( \Gamma \) exhibit narrow AMDs.

The temperature structure displays a very steep gradient at those values of the local gas column density \( N_{\text{HI}} \) where ionization instability occurs in the gas under constant pressure (Różańska et al. 2008; AD15). Below we describe the cloud structure in detail separately for these two different SEDs. Then, for a given SED, we explore how the cloud structure depends on the initial ionization parameter and the gas density.

3.1. SED A

The temperature variations across the depths of the clouds for group A SEDs are shown in Figure 3. The local column density \( N_{\text{HI}} \) is measured from the illuminated surface of the cloud. Steep drops at specific values of the column density are clearly visible. The number of steep temperature drops is one or two depending on the spectral slope of the incident hard X-ray component. The value of surface temperature, which is a result of thermal balance, differs by one order of magnitude, from \( 1.58 \times 10^8 \) to \( 1.58 \times 10^9 \) K, between the most extreme values of \( \Gamma \) values, i.e., 1.4 and 3.2. The corresponding values of the Compton temperature (mean photon energy of illuminating continuum) for those models are \( 1.75 \times 10^8 \) and \( 3.27 \times 10^8 \) K, respectively. As the value of \( \Gamma \) increases, the number of sudden temperature drops changes from two to one.

For \( \Gamma \leq 2.4 \), there are two distinct regions where a quick drop in the temperature occurs. However for \( \Gamma > 2.4 \), only a single temperature drop is seen since the temperature at the surface of the cloud is too low to form a well developed hot region. However, this division is very dependent on the SED shape and cannot be treated as a general behavior.

The sudden drops in the temperature are also nicely reflected by the switch in the number of prominent AMD dips, from two to one, in the corresponding shapes of AMDs in the group A models as shown in Figure 4 for selected values of \( \Gamma \). The models clearly demonstrate that the number of AMD dips depends on the slope of the illuminating X-ray power law. This effect is directly reflected in the value of temperature at the cloud surface, which is derived from the energy balance equation. When the X-ray-illuminated continuum is relatively harder (lower \( \Gamma \)), more energetic photons heat gas more strongly in photoionization and Compton or free–free processes.

The common feature seen in all AMDs for group A models, despite variations in \( \Gamma \), is that the overall normalization always remains at the level of a few \( 10^{21} \text{ cm}^{-2} \). This result is in very good agreement with the AMD normalization for Seyfert galaxies obtained from observations (Behar 2009; Dettmers et al. 2011). It also demonstrates that the AMD normalization...
3.2. SED B

The temperature structure in the case of SED B models as a function of photon index in the range $\Gamma = 1.4-3.2$ is shown in Figure 5. From this figure, a clear separation between two types of models is seen. For values of $\Gamma$ in the range 1.4–2.2, a large amount of absorbing material $\geq 2 \times 10^{23}$ cm$^{-2}$ is required in order to span the broad range of ionization levels and reach the minimum temperature. However, for values of $\Gamma > 2.2$, the total column density required is $\leq 10^{23}$ cm$^{-2}$. These clouds also have much a lower value of Compton temperature at the cloud surface. The value of Compton temperature for the hardest spectrum, $\Gamma = 1.4$, is $8.7 \times 10^3$ K, while for the softest spectrum, $\Gamma = 3.2$, it is $4.7 \times 10^4$ K.

We point out here that, for the same value of ionization parameter, SED A's illuminating continuum heats up the cloud to a temperature an order of magnitude lower compared to SED B. This fact clearly indicates that the ionization parameter is not a direct indicator of gas temperature; the shape of the SED of the ionizing photons that interact with the gas on the microscopic level has a major influence on the final thermal equilibrium. Furthermore, the large number of X-ray photons in SED B causes over-ionization of the gas, decreasing the number of ions that can produce absorption. Therefore, to achieve the observed quantity of absorbing ions, we need to increase the total column density. For this reason, the SED B models always require high values of total column density, $\sim 10^{23}$ cm$^{-2}$, more than an order of magnitude higher than those indicated by the observed AMD shape (Behar 2009; Detmers et al. 2011). This effect was demonstrated in a recent work by Adhikari et al. (2018b).

Figure 5. Thermal structure across clouds illuminated with SED B, for different values of $\Gamma$ in the range 1.4–3.2. Presented models are computed for $N_H$ large enough to reach the lowest temperatures on the non-illuminated side of the cloud. The values of $n_{H,0} = 10^5$ cm$^{-3}$ and $\xi_0 = 1.36 \times 10^4$ erg cm s$^{-1}$ at the cloud surface are fixed in these computations.

3.3. Ionization Parameter

AD15 successfully fitted the positions of two observed AMD drops with the CPT model, though just for case of Mrk 509. Since the aim of the current paper is to explain the the shape of the AMD in six sources as observed by Behar (2009), we assume group A SEDs hereafter. There may, of course, exist an intermediate SED shape (between A and B) which will yield the optimum match with the observed AMD. To extract that optimal SED shape, we would need to calculate a large number of models and use machine learning to compare models with observations, and we defer that process to a future work.

In this subsection, we present the influence of the values of ionization parameter and gas density assumed at the cloud surface on the overall AMD shape for group A SEDs. For that purpose we compared two values of $\xi_0$ an order of magnitude apart, $1.36 \times 10^4$ and $1.36 \times 10^5$ erg cm s$^{-1}$. In the case of the high value of $\xi_0$, relatively deeper gas layers are hot, of the order of Compton temperature. In this case, when ionization parameter decreases with depth, the temperature structure displays two steep drops as seen in Figure 6. In these models, we adopted $\Gamma = 2.0$, $n_{H,0} = 10^8$ cm$^{-3}$, and $\xi_0 = 1.36 \times 10^4$ erg cm s$^{-1}$ only when the total column density of the cloud is high enough that a deeper cold zone develops. In contrast, for the lower value of $\xi_0$, the deeper

Figure 6. Thermal structure across the cloud illuminated with SED A, $\Gamma = 2.0$. Models are computed for $n_{H,0} = 10^5$ cm$^{-3}$ and various values of $N_{H}$ as marked in the figure. The ionization parameter is always $\xi_0 = 1.36 \times 10^4$ erg cm s$^{-1}$.

Figure 7. Same as in Figure 6 but for a surface ionization $\xi_0 = 1.36 \times 10^5$ erg cm s$^{-1}$.
layers are not so hot, and the overall temperature structure displays at most one steep drop, as shown in Figure 7, for the same SED and gas density.

The number of drops in each case is nicely reflected in the shapes of the AMD, shown for the same two cases in Figures 8 and 9, respectively. When we start our computations with the higher value of $\xi_0$, two dips in the AMD are clearly seen, but the observations of the six sources do not cover the AMD at $\log \xi > 3.3$ (see Section 4). Therefore, to reproduce the data, it is useful to start the model with the lower value of $\xi_0$. This lower ionization parameter potentially provides the one prominent dip observed in the six AMDs. However, the dip observed in the AMDs is located at $0.8 < \log \xi < 1.7$, which is in strong disagreement with our model: the model AMD, shown in Figure 9, possesses one dip at $2 < \log \xi < 2.5$.

To confirm that thermal instabilities are responsible for the appearance of the dip in the AMD, we plot the stability curve, i.e., temperature versus dynamical ionization parameter $\Xi$ (Krolik et al. 1981), which relates to the parameter $\xi$ by

$$\Xi = \frac{P_{\text{tot}}}{P_{\text{gas}}} = \frac{\xi}{4\pi ckT}.$$  \hspace{1cm} (4)

For the AMD presented in Figures 8 and 9 we plot the corresponding stability curves in Figures 10 and 11, respectively. The dips in the AMD appear exactly at locations where unstable branches of the stability curve develop.

To explore the dip’s origin, we compare the major gas heating–cooling processes i.e., Compton and free–free, for two models of different ionization state, as shown in Figure 12. It is clear that when the ionization degree is higher i.e., $\xi_0 = 1.36 \times 10^4$ erg cm s$^{-1}$ (top panel), the Compton contribution to the cooling (red dashed line) is comparable to the free–free cooling (blue dashed line) at the surface of the gas cloud. The situation differs as we move to the lower ionization parameter, $\xi_0 = 1.36 \times 10^3$ erg cm s$^{-1}$ (bottom panel), where...
the Compton cooling contribution decreases by an order of magnitude. At the values of the ionization parameter corresponding to the positions of the AMD dips, sudden changes in the heating–cooling rates are also observed, as demonstrated in Figure 12. These positions correspond to the sudden temperature drops shown in the thermal structures in Figures 6 and 7, respectively.

In the case of the lower value of $\xi_0$ (bottom panel of Figure 12), there is only one sudden change present in the heating–cooling vertical cloud structure. These results are again confirmation that the AMD minima are caused by thermally unstable regions where an abrupt change in the heating–cooling processes also occurs. These unstable regions are located at the same range of ionization parameter inside the cloud (as indicated by the upper labels on both panels), independently from the value of this parameter at the front of the cloud. Therefore, the the value of the ionization parameter at the surface changes the number of dips in the AMD, but does not influence the position of those dips.

3.4. Gas Density

The last parameter that may influence the AMD dip position and depth is the gas density at the irradiated face of the cloud, $n_{H,0}$. To investigate this influence, all models considered here are computed with SED A, $\Gamma = 2.0$, and the same low ionization parameter $\xi_0 (1.38 \times 10^3 \text{ erg cm}^{-1})$, which yields one prominent dip in the AMD models. The only parameter we vary now is the value of the density at the illuminated face of the cloud. The calculations are done for values of $n_{H,0} = 10^8$, $10^9$, $10^{10}$, and $10^{11}$ cm$^{-3}$.

The cloud temperature structures, the corresponding AMD models, and stability curves are presented in Figures 13–15, respectively. There is no significant difference in the overall properties of the AMD for $n_{H,0} \leq 10^{11}$ cm$^{-3}$. For these models, only one AMD dip is present since the initial value of ionization parameter is already below the value $\xi \sim 3 \times 10^3 \text{ erg cm}^{-1}$, at which the first dip (counting from the cloud illuminated face) occurs in the AMD models. However, the depth of the AMD dips and the AMD normalization are slightly different even for these range of densities. With increased gas...
density, the depth of the AMD dip decreases and the overall normalization increases as seen in Figure 14. As the gas density becomes large ($10^{12}$ cm$^{-3}$), the AMD dip at $\xi \sim 200$ disappears and a continuous AMD is obtained for this model.

However, in all models we see a very strong decrease in the AMD below $\xi \sim 10$. This decrease is not followed by a recovery at further lower values of the ionization parameter since our computations for the assumed initial parameters stop when the gas reaches the very low temperature limit in the TITAN code, which is 8000 K. The examples we computed for normalization increases as seen in Figure 14. As the gas density, the depth of the AMD dip decreases and the overall normalization increases as seen in Figure 14. As the gas density becomes large ($10^{12}$ cm$^{-3}$), the AMD dip at $\xi \sim 200$ disappears and a continuous AMD is obtained for this model.

However, in all models we see a very strong decrease in the AMD below $\xi \sim 10$. This decrease is not followed by a recovery at further lower values of the ionization parameter since our computations for the assumed initial parameters stop when the gas reaches the very low temperature limit in the TITAN code, which is 8000 K. The examples we computed for the case of high gas density, i.e., $n_{H_0} \geq 10^{10}$ cm$^{-3}$, are already thick enough such that the temperature at the non-illuminated cloud face drops suddenly. From the temperature structure one may expect that the strong temperature drop that causes the strong decrease of the AMD below $\xi \sim 10$ is also caused by thermal instability. With the TITAN code, it is not possible to go deeper into the illuminated thick gas while allowing for a still higher total column density, since the required radiative and hydrostatic equilibrium is not achieved for thicker clouds. Therefore, in the case of the dense clouds presented in Figure 13, we are not able to reconstruct the stable branch of the cold gas, $\sim10^4$ K. Additional processes (probably many more line transitions) should be included in the radiative transfer calculations to solve this problem, and we leave this issue to be addressed in a future work.

The importance of Compton, free–free, bound–free (ionization and recombination) and bound–bound (lines) heating/cooling rates for each model with illumination by SED A and with different gas densities is shown in Figure 16. The figure demonstrates that the physical reason for this AMD behavior is reflected in the domination of cooling and heating processes across the cloud. For gas at lower density, $10^8$ cm$^{-3}$ (left panel), there is a clear domination of Compton heating over free–free heating. When the density at the cloud surface increases, the dominance of free–free heating over the Compton heating is clearly visible inside the cloud for $n_{H_0} \geq 10^{11}$ cm$^{-3}$ (second panel from the left), and even at the surface of the cloud for densities $10^{11}$ and $10^{12}$ cm$^{-3}$ (two right panels). For $n_{H_0} \geq 10^{11}$ cm$^{-3}$ the free–free domination occurs across the whole absorber. The sum of ionization and line heating is roughly linear across the clouds. Only the line heating rate decreases strongly on the non-illuminated face of the cloud, but it is 1.5 orders of magnitude lower than the ionization heating rate.

All dips in the AMD are related to the rapid change in the heating/cooling mechanism with density, as shown here for the $\xi \sim 200$ feature, but they are less easy to demonstrate. The dip at higher $\xi$ which appears in Figure 8 is related to the increased emission line cooling in comparison with Compton cooling, and the dip at $\xi \sim 10$ is related to the onset of heating mostly through numerous lines from atoms and (perhaps) molecules.

The change of the dominant heating mechanism from Compton heating to free–free heating with a decrease in density may be connected with wind launching mechanisms. When density is relatively low, we deal with Compton-heated winds, but for higher density we may encounter thermally driven winds. However, this hypothesis needs further consideration.

4. Comparison with Observed AMDs

In AD15, the authors demonstrated that the observed AMD of Mrk 509 (Detmers et al. 2011) can be explained by the absorber being under CTP. The two dips obtained in the AMD model are in excellent agreement with the position of the observed AMD dips. Nevertheless, the normalization of the AMD in the best-fit model was higher by a factor of $\sim 30$ than the observed AMD normalization.

Figure 17 shows a comparison between the observed AMDs for six Seyfert 1 galaxies published by Behar (2009) and our best-fit model computed with SED A with $\Gamma = 2.0$, $\xi_0 = 1.38 \times 10^4$ erg cm$^{-2}$ s$^{-1}$, and $n_{H_0} = 10^{12}$ cm$^{-3}$. The model is binned in order to reconstruct the limited resolution of the observed AMD, which is always approximated by a step function (Holczer et al. 2007). The figure demonstrates that there is a very good agreement in the overall AMD normalizations ($\sim 10^{21}$ cm$^{-2}$) of those sources and our model.

Interestingly, observed multi-wavelength spectra obtained by different instruments are available for these six sources. The coverage is still poor, but the optical–X-ray index $\alpha_{OX}$ was found for three sources by full spectral fitting and correcting for absorption. These values are: $-1.4$ for NGC 3516, $-1.31$ for NGC 3783, and $-1.25$ for NGC 5548 (Vasudevan & Fabian 2009), and suggest B-type SEDs (see Table 1). On the other hand, bolometric luminosities of those sources, determined from luminosity measured at 5100 Å, span from $10^{43}$ erg s$^{-1}$ (except NGC 3516, which has a luminosity $1.6 \times 10^{43}$ erg s$^{-1}$). Combining with measured black hole masses, such luminosities suggest the accretion rates relative to Eddington span 0.06 to 0.3, and this fact supports instead the SED A case. Therefore, our result on AMD shape is not fully supported by the observed SED shapes for these sources. We conclude here that there are some intermediate shapes of SEDs between A and B, which can provide the observed AMD shape. We plan to use them in our photoionization simulations in future works.

5. Discussion

Our computations indicate that, for densities higher than $10^{10}$ cm$^{-3}$, free–free processes dominate over Compton processes, and both thermally unstable zones caused by ionization of heavy elements are almost completely suppressed. To reconstruct the full shape of the AMD also in the low-ionization band as well, we should include radiation processes occurring in low-temperature dense gas. Nevertheless, from our
Goosmann et al. (2016) for NGC 3783’s WA. Therefore, only a part of the AMD drop is reconstructed here, but we show that the position of the dip is well reproduced, and the overall normalization matches the observational data.

Prior AMD modeling by Stern et al. (2014) assumed that the WA is compressed by radiation pressure (RPC) using the numerical code CLOUDY. However their RPC models did not reproduce the AMD dips that are caused by the thermal instability operating in the AGN photoionized outflow. In our opinion, this is related to the issue that the transfer of radiation in CLOUDY is done using an escape probability method in a one-stream approach, integrating gas from the front to back side of the cloud. This method does not calculate the local radiation pressure while computing the cloud structure under CTP. However in TITAN, the radiative transfer is done using the ALI method, where the proper source function term in the radiative transfer equation is taken into account. Since the computations are done on a much denser grid, and in the so called two-stream approach for radiative transfer computations, we are able to enter the few points in the thermally unstable region demonstrated in previous sections.

It is known that the precise description of the transition between the hot and cold thermally stable gas through the thermal instability zone is possible only when thermal conduction is taken into account (Różańska 1999), but in this case radiative equilibrium becomes a second-order differential equation, and computations become extremely complicated. Thermal instability occurs when the radiative (energy) balance equation has three solutions: stable hot, stable cold, and intermediate/unstable. In a geometrically narrow zone inside a cloud, all three solutions are available as a result of a subroutine solving local energy balance. By default, the TITAN code uses a two-stream approximation, and it computes the transfer from top and bottom and iterates to merge both results. But if we want to follow only the hot or only the cold solution, there is such an option in the code. Such simulations were done by Czerny et al. (2009), but further improvement can be made when thermal conduction or evaporation is included in the code (Różańska 1999).

Nevertheless, to combine the radiative transfer algorithm with thermal conduction and gas dynamics (i.e., evaporation) is very challenging and extremely time-consuming, and such tasks are left to future work with the development of new computational methods. This method was also used by Goosmann et al. (2016) in the case of the Seyfert galaxy NGC 3783, where the authors were able to indicate the

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**Figure 16.** Heating and cooling processes operating in the gas clouds described by the parameters given in Figure 13. The panels from left to right represent gas densities from $10^8$ cm$^{-3}$ to $10^{12}$ cm$^{-3}$. Bound–free (ionization and recombination) and bound–bound (lines) processes stay constant over the cloud structure. The free–free heating–cooling processes become more significant in relatively higher-density gas.

**Figure 17.** Best-fit AMD model (shown by a black histogram) computed with constant total pressure assumptions in the TITAN code overplotted with the observed AMD points obtained by Behar (2009) for six Seyfert 1 galaxies. The AMD model parameters are: SED A with $\Gamma = 2.0$, $\xi_0 = 1.38 \times 10^2$ erg cm s$^{-1}$, and $n_{H,0} = 10^{12}$ cm$^{-3}$, the last two defined at the cloud surface.

comparison in Figure 17, the similarity in overall shape between the modeled and observed AMDs is very encouraging and clearly demonstrates that the CTP models are very successful in explaining the WA properties in Seyfert galaxies. The requirement of high-density gas suppresses the high $\xi$ dip, but we see its only onset in the models. Nevertheless, we cannot increase the total column thickness since it is limited by the overall value of AMD normalization. In such a situation the TITAN code does not allow us to reconstruct the AMD below $\xi \sim 4.5$ erg cm s$^{-1}$ (this value depends on initial cloud parameters). From the very beginning, the TITAN code was developed for X-ray-illuminated hot gas and is not suitable for reconstructing gas below a temperature 8000 K due to the lack of relevant radiation processes. The code does not take into account that the radiation is in thermal equilibrium with cold matter which contains dust. The same result was obtained by

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**Table**: Rates (erg cm$^{-3}$ s$^{-1}$) for different processes in TITAN code. The panels from left to right represent gas densities from $10^8$ cm$^{-3}$ to $10^{12}$ cm$^{-3}$. Bound–free (ionization and recombination) and bound–bound (lines) processes stay constant over the cloud structure. The free–free heating–cooling processes become more significant in relatively higher-density gas.
appearance of the thermal instability, but they did not reconstruct the depth of dips in the AMD. The authors found that an AMD model with ionization parameter in the range 4000–8000 erg cm s\(^{-1}\) represents the observed AMD most closely, when the hot solution in TITAN is adopted. Moreover, the authors do not discuss how their models are sensitive to the gas density adopted in the computations.

### 6. Conclusions

In this paper, we studied the properties of WA clouds in AGN outflows by performing photoionization simulations using the numerical code TITAN (Dumont et al. 2000). We considered two types of SEDs illuminating the WA, which we divided into group A and group B (Adhikari et al. 2018b). Computations were done under the assumption that the total pressure inside the cloud, i.e., \(P_{\text{gas}} + P_{\text{rad}}\), is constant. The temperature and ionization structures were computed to obtain the AMD for each model.

The temperature structure for different SED shapes indicates that for models dominated by a strong optical UV bump and weak X-ray component, i.e., SED A, the normalization of the AMD derived with CTP models is of the order of a few \(\times 10^{12}\) cm\(^{-2}\), which is in excellent agreement with the observationally obtained average AMD normalization for six Seyfert 1 galaxies by Behar (2009).

When the disk luminosity is equal to or smaller than that of the X-ray power law i.e., SED B, the normalization of the AMD is 1.5 orders of magnitude higher than the normalization as determined by observations, and these SEDs are thus not favored for the modeled sources. We would like to point out that, while rejecting SED B is physically motivated, the adoption of SED A does not exclude an intermediate spectral shape between A and B, which will also result in adequate AMD normalization. However, to extract the optimal spectral shape responsible for the observed AMD, we would need to calculate a large number of models and to use machine learning to compare those models with observations. We plan to do this in a future work.

We have shown, for the first time, how varying the SED shapes within group A influences the AMD distribution due to having different shapes for the stability curve, a consequence of temperature structure, as presented in Section 3. This is in agreement with previous studies on the influence of SED on the overall gas ionization stability curve due to illumination (Chakravorty et al. 2009, 2012; Dyda et al. 2017).

For the first time we have specified how the AMD shape depends on the intrinsic gas number density. We conclude that the overall shape of the modeled AMD agrees with that from observations for high-density gas since a high density is needed to suppress the dips in the AMD at relatively high values of the ionization parameter. The agreement suggests that the WA in Seyfert galaxies typically has a density of the order of \(10^{12}\) cm\(^{-3}\) which is in agreement with the upper limit given by Elvis (2017) for a WA’s low-ionization phase. The high-density requirement may indicate that the WA is formed from the upper layers of the disk atmosphere. Similar high-density gas was recently found to be present in the broad- and intermediate-line regions (Hryniewicz et al. 2012; Adhikari et al. 2018a; Panda et al. 2018). Nevertheless, the gas velocities inferred from broad lines in the optical/UV domain are considerably higher—approximately 3–100 times higher—than those from the WA medium as derived from individual observed lines. This fact suggests different locations for both absorbers or different turbulent velocity gradients occurring in those media (Fukumura et al. 2010a, 2010b). The high density of the WA, as inferred from this paper, only means that the gas may originate from accretion disk atmospheres, which are dense. The question of what speeds up the outflows, which we observe as a line-of-sight absorbing material, is still not fully answered; it can be magnetic field or radiation pressure.

Our result for the high-density WA puts tighter constraints on the wind location. Assuming a typical Seyfert 1 luminosity to be \(10^{45}\) erg s\(^{-1}\), the location of such a dense cloud could be estimated at \(r \sim 10^{15}\) cm, which is about 30 gravitational radii for a black hole mass of \(10^8 M_\odot\). This location is very close to the SMBH and the question arises whether such a WA can survive in the very hostile innermost AGN region. The derived distance of 30 gravitational radii based on the ionization parameter comes with the assumption of point source radiation. Using a thin disk model it is straightforward to determine that thermal hydrogen ionizing radiation is effectively emitted even four times farther compared to this radius. Thus in this region the radiation is extended, which makes distance estimation more uncertain.

X-ray magnetic flares above an accretion disk were proposed by several groups (Czerny & Goosmann 2004; Ponti et al. 2004), which may be a mechanism for formation of hot ionized gas clouds. Nevertheless, the estimation of the lifetime for such clouds is not very optimistic. As per work by Goosmann et al. (2006), flares can live only 10 orbital periods, which gives a lifetime of the order of several weeks (months). In this situation the WA will be highly variable and unstable, in contradiction to what we really observe in 50% of AGNs. On the other hand, the existence of clouds of that density and location were postulated by Lawrence (2012) to explain the apparent UV peak at 1100\AA\ present in many AGN continua. More studies of the variability, including a UV part where emission from these clouds is expected to be seen, may shed more light on the probability of this scenario.

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*Software:* TITAN (Dumont et al. 2000).

**ORCID iDs**

T. P. Adhikari [https://orcid.org/0000-0003-4586-0744](https://orcid.org/0000-0003-4586-0744)

A. Różańska [https://orcid.org/0000-0002-5275-4096](https://orcid.org/0000-0002-5275-4096)

B. Czerny [https://orcid.org/0000-0001-5848-4333](https://orcid.org/0000-0001-5848-4333)

**References**

Adhikari, T. P., Hryniewicz, K., Różańska, A., Czerny, B., & Ferland, G. J. 2018a, ApJ, 856, 78

Adhikari, T. P., Różańska, A., Czerny, B., Hryniewicz, K., & Ferland, G. J. 2016, ApJ, 831, 68

Adhikari, T. P., Różańska, A., Hryniewicz, K., & Czerny, B. 2018b, in XXXVIII Polish Astronomical Society Meeting 7, ed. A. Różańska (Warsaw: Polish Astronomical Society). 322

Adhikari, T. P., Różańska, A., Hryniewicz, K., Czerny, B., & Ferland, G. J. 2017, FrASS, 4, 19

Adhikari, T. P., Różańska, A., Sobolewska, M., & Czerny, B. 2015, ApJ, 815, 83
