ABSORPTION MEASURE DISTRIBUTION IN Mrk 509

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ABSTRACT

In this paper we model the observed absorption measure distribution (AMD) in Mrk 509, which spans three orders of magnitude in ionization level with a single-zone absorber in pressure equilibrium. AMD is usually constructed from observations of narrow absorption lines in radio-quiet active galaxies with warm absorbers. We study the properties of the warm absorber in Mrk 509 using recently published broadband spectral energy distribution observed with different instruments. This spectrum is an input in radiative transfer computations with full photoionization treatment using the TITAN code. We show that the simplest way to fully reproduce the shape of AMD is to assume that the warm absorber is a single zone under constant total pressure. With this assumption, we found theoretical AMD that matches the observed AMD determined on the basis of the 600 ks reflection grating spectrometer XMM-Newton spectrum of Mrk 509. The softness of the source spectrum and the important role of the free–free emission breaks the usual degeneracy in the ionization state calculations, and the explicit dependence of the depths of AMD dips on density open a new path to the density diagnostic for the warm absorber. In Mrk 509, the implied density is of the order of $10^{8}$ cm$^{-3}$.

Key words: galaxies: active – galaxies: individual (Mrk 509) – instabilities – methods: numerical – radiative transfer

1. INTRODUCTION

There is a general consensus based on high-resolution X-ray data that the majority of the Seyfert galaxies contain ionized absorbing gas in their lines of sight. After the advancements in the observing X-ray instrumentation as Chandra, XMM-Newton, Suzaku, the extensive studies of the Warm Absorber (hereafter WA) in the active galactic nucleus (AGN) were performed. Many narrow absorption lines from highly ionized elements, detected with the use of gratings, provided a great opportunity to study this warm material (Collinge et al. 2001; Kaspi et al. 2001; Kaastra et al. 2002; Behar et al. 2003; Blustin et al. 2003; Krongold et al. 2003; Netzer et al. 2003; Steenbrugge et al. 2003; Yaqoob et al. 2003; Różańska et al. 2004; Turner et al. 2004; Steenbrugge et al. 2005; Costantini et al. 2007; Winter & Mushotzky 2010; Winter et al. 2012; Tombesi et al. 2013; Laha et al. 2014, and many other papers).

Some physical parameters of WA were estimated, but some are still difficult to constrain. From energy shifts of line centroids, it was found that the absorbing matter is systematically outflowing with velocities in the range $10^{5}–10^{7}$ km s$^{-1}$ (Kaspi et al. 2001; Kaastra et al. 2002). Directly from observations, ionic column densities of particular ions could be found and they are typically of the order of $10^{15}–18$ cm$^{-2}$. In the next step, by assuming a separate ionization zone for each ion, it is possible to calculate the equivalent hydrogen column densities, knowing the ion’s ionization fraction from photoionization codes such as CLOUDY, XSTAR, SLAB, and XABS. Such equivalent hydrogen column densities are in the range of $10^{18}-22$ cm$^{-2}$ (Steenbrugge et al. 2005; Costantini et al. 2007).

Moreover, those densities correspond to the continuous change of the ionization parameter $\xi$ (see Equation (1) for definition), which spans the range of a few decades, $\log(\xi) \sim -1$ up to 4.

Since then, several attempts have been made to model the continuous ionization structure of the WA in several AGNs (Holczer et al. 2007; Behar 2009; Detmers et al. 2011). Furthermore, Holczer et al. (2007) proposed to describe ionization structure of the wind by showing absorption measure distribution (AMD) obtained by a derivative formula (Equation (5) in this paper). These authors, for the first time, have shown that in the case of the source IRAS 13349+2438, AMD obtained from observations has a deep minimum in column density that is consistent with the negligible absorption of gas with log($\xi$) between 0.8 and 1.8. Such deep minima are present in AMD of other objects as well (see, for instance, Behar 2009; Detmers et al. 2011; Stern et al. 2014), and they are interpreted as observational evidence for thermal instability in a given ionization and the temperature regime.

To reproduce the observed AMD theoretically, we should consider the continuous ionization structure of WA in such a way that we can obtain proper normalization of the AMD function. This has been done recently by Stern et al. (2014) assuming a radiation pressure confinement (hereafter RPC) of the WA material. The authors considered that the WA consists of the stratified clouds, for which $P_{\text{gas}}$ increases gradually with the decrease of $P_{\text{rad}}$. The exponential decrease of the radiation pressure is caused via absorption on the material when the distance from the illuminating source, i.e., the active nucleus, gradually increases. The authors were successful in reproducing the normalization and the slope of AMD for Sy1 galaxies by showing the comparison of the model with observational points of AMD for the six best studied sources. Nevertheless, they were not able to quantitatively reproduce the deep minimum in column density for those six objects present in the log $\xi$ between 0.8 and 2.

In this paper, we show how AMD for the Sy1.5 galaxy Mrk 509 can be successfully reproduced by the WA being under the condition of constant total pressure, which is a sum of gas and radiation pressure (Gonçalves et al. 2006; Różańska et al. 2006). The radiation pressure is computed from the
radiation field at each point of the computations and it is added to the gas pressure. We neglect other pressure components, for instance, the magnetic one. We used the broadband spectral energy distribution (SED) of Mrk 509 from the paper of Kaastra et al. (2011, hereafter K11) to represent the radiation illuminating the WA cloud. Assuming the plane parallel geometry, we carried the simulations using the TITAN photoionization code (Dumont et al. 2000). By assuming constant total pressure, the matter of the WA is self consistently stratified without any additional requirements. The decrease of the radiation pressure is self-consistently computed within the photoionization code TITAN and occurs due to absorption and emission i.e., all possible interactions of radiation field with matter. Since exact radiative transfer is computed, radiation pressure self-consistently influences the matter structure. For the differences between the escape probability mechanism and exact radiative transfer calculations, we refer readers to the paper by Dumont et al. (2003).

Since the radiation field influences the matter structure and eventual thermal instabilities, the S-curve, which is the dependence of the temperature $T$ on the dynamic ionization parameter $\Xi$ (Equation (2) for definition), can be fully constructed with the use of a single cloud and with TITAN calculations (Różańska et al. 2006). In this paper, we compare results obtained with two codes, TITAN and CLOUDY, for exactly the same physical input: SED of Mrk 509 as the incident radiation. The two codes differ in the way they treat the radiative transfer, and only with the use of TITAN we managed to compute thermally unstable regions and fully reproduce deep minima in the observed AMD of Mrk 509 (Detmers et al. 2011).

This result is a direct proof that thermal instabilities are responsible for the deep minimum in the column densities of AMD. Moreover, it provides strong evidence that the WA in AGNs is compressed by radiation pressure, and it should be modeled with proper treatment of this effect.

The overall structure of the paper is as follows. Section 2 contains information about the incident radiation shape we used in photoionization calculations. The description of the photoionization codes and results of the photoionization calculations are given in Section 3. In Section 4, we present the method of determining AMD from observations and calculating AMD from our models. Finally, we compare our theoretical AMD with the observational data. The conclusions are presented in Section 5.

2. MRK 509 AND ITS SPECTRAL SHAPE

Mrk 509 with a redshift of 0.034397 (Huchra et al. 1993), is one of the best studied local AGNs, with exceptionally high luminosity $L(1-1000 \text{Ryd}) = 3.2 \times 10^{45} \text{erg s}^{-1}$ classified as a Sy1 galaxy. It is usually considered to be one of the closest QSO/Sy1 hybrids. Peterson et al. (2004) have reported that Mrk 509 harbors a super massive black hole of mass $1.4 \times 10^8 M_\odot$.

The WA in this source was extensively studied with the 600 ks reflection grating spectrometer (RGS) on board the XMM-Newton X-ray telescope (Detmers et al. 2011; Kaastra et al. 2012). The few tens of absorption lines from highly ionized metals were identified, allowing for the determination of ionic column densities. Furthermore, equivalent hydrogen column densities were calculated for each ion, and AMD was constructed (Detmers et al. 2011). Additionally, the upper limits on the location of different ionization phases of the WA were estimated, using the variability method, which requires the assumption that any observed changes are caused by changes in the ionization states (Kaastra et al. 2012). Those authors reported that observed ionization components span the distance upper limits from 5 to 400 pc.

For any consistent photoionization calculations of WA, the broadband SED of the source is crucial. It was shown by Różańska et al. (2008) that if the SED of an AGN is dominated by a soft component (i.e., an accretion disk), the stability curve obtained during photoionization calculations differs substantially from that obtained with the AGN SED dominated by a hard-X-ray power-law component. The authors also explained that this is due to the fact that in the case of soft radiation entering the WA, bremsstrahlung is the dominant cooling in the cloud, while in the case of hard-X-ray illumination, Compton scattering is responsible for high-temperature equilibrium in the WA. A systematic study of how the stability curve depends on the shape of the incident SED was done by Chakravorty et al. (2009). In particular, the authors discussed the influence of the soft-X-ray excess on the shape of the stability curve in this paper. Additionally, chemical abundances affect the ionization balance of the WA (Hess et al. 1997), and hence also the shape of the resulting stability curve. Nevertheless, for this paper, we assume solar chemical abundances, and we keep them constant during all photoionization calculations.

Recently, the very detailed observed continuum spectral shape of Mrk 509 was published by K11. The spectrum was obtained during their multi-wavelength campaign of several observations taken in various energy bands, with XMM-Newton: RGS, EPIC (pn, MOS), and OM. Simultaneously with XMM-Newton observations, data with INTEGRAL was also obtained to observe the hard X-rays. Additionally, they collected the data of Mrk 509 with Chandra LETGS together with the Hubble Space Telescope COS UV detection. Moreover, the observation of Mrk 509 was done with Swift, using both the instruments XRT and UVOT. For the final construction of SED, the authors used IR points from IRAS and Spitzer data, but it is unclear how much IR emission is seen by the outflow. This is because the wind is most likely located closer to the black hole than the dusty torus from which most of the IR radiation originated.

K11 allowed us to use those points for our project. The SED of Mrk 509 covers a wide range of the wavelength band, which is essential for obtaining the ionization balance needed for photoionization modeling. All observed spectral points are presented in Figure 1 as red circles. Mrk 509 has one of the best spectra covering broadbands among all of the well studied AGNs. The black line on the same figure demonstrates the incident SED used by us in photoionization calculations by the TITAN and CLOUDY codes. Both codes allow for the input of the incident spectrum by points and the linear interpolation is done in order to fully define the incident continuum that goes into the simulations.

3. PHOTOIONIZATION CALCULATIONS

Here, we study the detailed structure of the WA cloud using the photoionization codes TITAN (Dumont et al. 2000) and CLOUDY 13.02 (Ferland et al. 2013) with the same initial physical conditions. Although both codes are used to study the clouds subjected to the incident radiation emanating from the central source, they do differ in their assumptions of radiative
Figure 1. Spectral energy distribution of Mrk 509. The black line corresponds to the incident spectrum, which is the input to the photoionization codes TITAN and CLOUDY (see the text for an explanation). The red circles are the points adapted from K11 and normalized to incident flux at the corresponding inner radius of the cloud.

transfer treatments and the number of spectroscopic lines considered. Nevertheless, the general idea is the same. Both codes solve radiation transfer through the gas in thermal and ionization equilibrium with the non-LTE equation of state.

The most important difference between codes is that CLOUDY uses the escape probability mechanism to solve radiative transfer, while TITAN uses the Accelerated Lambda Iteration (ALI) method (Collin et al. 2004), which is more accurate in optically thick media. The detailed comparison of both radiative transfer methods in the context of X-ray absorbing gas was done in Dumont et al. (2003). Below, we show and compare the output of two codes in the case of our particular source Mrk 509 and its warm absorber.

The following assumptions are made for this modeling in both photoionization codes. The geometry of the cloud is set to the plane parallel. The expression for the ionization parameter $\xi$, at the irradiated surface of the cloud relating to the distance from the illuminating source $R$ is

$$\xi = \frac{L_{\text{ion}}}{nR^2},$$

where $L_{\text{ion}}$ is the luminosity of the ionizing source and $n$ is the hydrogen number density. The luminosity can be obtained from observations, whereas the number density and ionization parameter are free parameters in our calculations.

### 3.1. TITAN Computations

TITAN was developed by Dumont et al. (2000) and was mainly designed to determine the structure of temperature and ionization state and the continuum emission spectrum of a thick hot photoionized slab of gas. Using this code, the physical state of the gas is computed at each depth, assuming the local balance between the ionization and recombination of ions, excitation and deexcitation, local energy balance, and finally total energy balance. TITAN assumes the transfer of both continuum and lines using the ALI method, which precisely computes line and continuum intensity self-consistently. There are many options to control the physical properties of the absorbing gas. Here, to calculate the stability curve, which is compared to the CLOUDY code (Section 3.3), we use the assumption of the constant density slab, but, for the explanation of AMD in Mrk 509, we reject this assumption and compute the more realistic constant total pressure cloud (see the results in Section 4). This exercise is made to ensure the reader, that stability curves calculated by both codes agree for the same physical conditions of the gas.

For the purpose of this paper, we make a stronger assumption that the total pressure (i.e., gas and radiation pressure: $P_{\text{gas}} + P_{\text{rad}}$) is held constant throughout the plane parallel slab of the gas, and the volume density and ionization parameter across the cloud are stratified. The assumption of constant pressure allows the ionized gas to be naturally stratified due to illumination, as discussed in (Różańska et al. 2006). The computations of all the structure are done iteratively until the convergence is reached.

In the constant total pressure model, plane parallel geometry is considered, and the radiation source is assumed to hit the cloud perpendicular to the surface. The parameters of the model are the ionization parameter $\xi_0$, and the hydrogen number density $n_0$ (both defined at the illuminated cloud surface), the total column density $N_H$, and the incident SED. Although the ionization parameter is well constrained in the surface of the illuminated cloud, ionization properties are continuously changing as we go deeper into the cloud. This happens since all thermodynamical parameters, such as gas temperature, gas density, and the radiation pressure, do change with the depth of the cloud. To trace this behavior, the dynamic ionization parameter, $\Xi$ is defined as

$$\Xi = \frac{\xi}{4\pi c k T} = \frac{L_{\text{ion}}}{4\pi c R^2 n k T} = \frac{F_{\text{ion}}}{c P_{\text{gas}}} = P_{\text{rad}}/P_{\text{gas}},$$

where $F_{\text{ion}}$ is the flux affecting the cloud, $c$ is a velocity of light, and $T$ is the temperature of the gas. Here, we do not follow the standard convention that $P_{\text{gas}}$ only accounts for the hydrogen density number $n$. For fully ionized gas, with heavy element abundance, the total density number equals $\approx 2.3 \times n$, and if the gas pressure is computed with total density, the factor $2.3$ should be taken into account, as it is in the basic definition of $\Xi$, given by Krolik et al. (1981). Nevertheless, since the observers do not use the value of density while determining AMD from observations, we compute the current value of $\xi$ using the temperature, the radiation pressure, and the gas pressure, which directly comes out from our code.

All thermodynamical parameters describing the cloud structure as temperature, radiation pressure, hydrogen, and total density numbers are given as functions of the distance from the illuminating source. Therefore, we can self-consistently compute both ionization parameter and its change with the distance from the cloud illuminated surface, using the value of radiation pressure computed from the second moment of the radiation field.

### 3.2. CLOUDY Computations

Cloudy is a well documented public code extensively used in the calculation of the photoionization in many different clouds surrounding planetary nebulas, in the interstellar medium and active galaxies. It has an extensive explanation of the physics of the plasma subjected to different perturbations given in well...
organized books (Hazy1 and Hazy2). The same as in TITAN runs for cloudy calculations, we assumed the open geometry with thin plane parallel zones. All other input parameters, such as the incident SED, the ionization parameter, the inner radius, the total column density of the slab, and the hydrogen density at the surface of the illuminated cloud are the same in both codes. We did this simulation for many grids of densities. The default option in cloudy is the constant density through the spherical geometry computed with cloudy is presented by the solid magenta line.

3.3. Stability Curves for Constant Density Clouds

The general way for the analysis of the stability of the cloud subjected to the incident radiation from the central source is to study a stability curve, i.e., temperature as a function of the ratio of the radiation pressure to the gas pressure, which is a dimensionless parameter $\Xi$ (Equation (2)). Such a defined stability curve can be computed in several ways. The most natural way is to compute a grid of constant density clouds located at the same distance from the illuminated source. By changing the cloud density, we change the ionization parameter and thus the gas temperature of the cloud. In Figure 2, we compare stability curves computed in this way by two photoionization codes cloudy (cyan triangles), and TITAN (magenta squares). Both codes use the parameter selection of the clouds tabulated in Table 1. For each calculation, we considered the source luminosity $3.2 \times 10^{45}$ erg s$^{-1}$ and the inner radius of the cloud, i.e., the distance between the source and the illuminated face of the cloud is taken as $\log(r_0/cm) = 17.25$.

In the case of extended envelopes, the radiation pressure changes while we go deeper into the cloud due to geometrical dilution and absorption by ionized gas. Therefore, in principle, it is possible to calculate an extended, spherically symmetric cloud at constant density. While entering deeper inside the cloud, the luminosity decreases as a distance square, and ionization parameter of the consecutive zone decreases. A full stability curve can also be reconstructed in this way, as presented in Figure 2 by the magenta solid line.

All curves agree for temperatures down to $3 \times 10^4$ K. Below this temperature, atomic data, which are different in the two codes, may cause some inconsistencies. However, since we concentrate here on the warm absorbers, we may consider that both codes work perfectly in the considered temperature regime.

3.4. Stability Curves for Constant Pressure Clouds

As shown in Figure 3, the constant pressure stability curves form TITAN and cloudy shows a similar trend except for the considerable difference in the thermal instability zone. Thermal instability zones are part of the stability curve where the slope is negative. The main difference between the two codes here is that cloudy is unable to compute the structure at the zones of instability (there are no points on the unstable branch of the stability curve). The stability curve computed by TITAN shows several points on the unstable branch. Also, there is a difference in the range of the ionization parameter at which the instability occurs. Such a difference may be due to the different approximations used in the code to solve thermal balance equation and the differences in the atomic database used.

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**Table 1**

| Codes Used | $n_0$ (cm$^{-3}$) | $\xi_0$ (ergs cm s$^{-3}$) | Geometry |
|------------|-----------------|----------------------|----------|
| TITAN      | $10^2$–$10^{12}$ | as $L/n_0^2$        | plane parallel |
| cloudy     | $10^2$–$10^{12}$ | as $L/n_0^2$        | plane parallel |
| cloudy     | $10^4$          | $10^{11}$           | Spherical |

*Note.* When the range of densities is shown that means the grid of clouds were calculated. The inner cloud radius in all cases is $\log(r_0/cm) = 17.25$.  

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http://nublado.org/
4. ABSORPTION MEASURE DISTRIBUTION

The distribution of the absorbing column in the line of sight is often described as AMD. Almost always, the large range of density is measured, the AMD can be described self-consistently. It is not possible to get the hydrogen column density directly from observation since we do not see hydrogen lines. It is derived using the ionization parameter of each element, and the ionization parameter value required to produce the observed feature. In nature, there is a distribution of gas with different ionization states. For instance, the density at the illuminated face of the gas H, which may account for absorption in the line, and, in reality, one must take into account the full dependence of $f_{\text{ion}}$ on $\xi$. This means that when ion density for individual warm absorbers are measured, the AMD can be derived from the following formula.

$$N_{\text{H}} = A_{Z_{\odot}} \int \text{AMD} f_{\text{ion}}(\log \xi) d(\log \xi).$$

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$$N_{\text{ion}} = A_{Z_{\odot}} \int \text{AMD} f_{\text{ion}}(\log \xi) d(\log \xi).$$

For the detailed investigation of the effect of the density on the AMD structure, we made several runs with densities $n_0 = 10^5$, $10^6$, and $10^7$ cm$^{-3}$, as presented in Figure 4 (the density $n_0 = 10^7$ cm$^{-3}$ is removed from the figure for clarity). For lower values of the density at the illuminated face of the cloud $n_0$ up to $10^5$ cm$^{-3}$, the position of the dips remains the same. For higher densities, the position of dips in AMD changes. This is connected with the fact reported by Różańska et al. (2008) that photoionization models with high densities similar to those in the broad line region (BLR) are not degenerated any more when the SED of the central source is dominated by a strong optical/UV component. This is the case for Mrk509. The physical reason for this is that, in the case of the hard incident spectrum, all radiative processes (Comptonization, line heating/cooling) are linear in density and the solution is determined by the ionization parameter, independently from the local density. However, for soft incident spectra the bremsstrahlung plays an important role, and the quadratic dependence of the bremsstrahlung (free–free) on the density breaks the degeneracy and introduces a dependence on the density (Różańska et al. 2008).

As can be seen from Figure 4, when the densities are comparable to the Narrow Line Region (NLR) densities, the two dips remain prominent almost around the same range of ionization states. As we move toward the regime where the density is comparable to the BLR density, i.e., at $n_0 = 10^9$ cm$^{-3}$, there is only one prominent dip present.

### 4.1. Modeled AMD for Mrk 509

We used the titan photoionization code to reproduce AMD for Mrk 509 assuming that the absorbing cloud is in total pressure equilibrium (Różańska et al. 2006). When a cloud is irradiated with the incident SED of the source, the total pressure equilibrium requirement self-consistently provides the distribution of the ionization parameters for which the AMD is calculated. Note, that when we compute AMD from simulations, we compute $\xi$ at each depth by the following relation.

$$\xi = 4 \pi c k T \frac{P_{\text{rad}}}{P_{\text{em}(0)}} = 4 \pi c \frac{P_{\text{rad}}}{n}.$$

Our model of constant pressure reproduces the AMD derived observationally by Detmers et al. (2011). Both discontinuities seen in the distribution of AMD in their paper are reproduced using our model. We carried out several exercises to determine how the AMD behaves with different parameters and the results are as follows.

For the detailed investigation of the effect of the density on the AMD structure, we made several runs with densities $n_0 = 10^5$, $10^6$, and $10^7$ cm$^{-3}$, as presented in Figure 4 (the density $n_0 = 10^7$ cm$^{-3}$ is removed from the figure for clarity). For lower values of the density at the illuminated face of the cloud $n_0$ up to $10^5$ cm$^{-3}$, the position of the dips remains the same. For higher densities, the position of dips in AMD changes. This is connected with the fact reported by Różańska et al. (2008) that photoionization models with high densities similar to those in the broad line region (BLR) are not degenerated any more when the SED of the central source is dominated by a strong optical/UV component. This is the case for Mrk509. The physical reason for this is that, in the case of the hard incident spectrum, all radiative processes (Comptonization, line heating/cooling) are linear in density and the solution is determined by the ionization parameter, independently from the local density. However, for soft incident spectra the bremsstrahlung plays an important role, and the quadratic dependence of the bremsstrahlung (free–free) on the density breaks the degeneracy and introduces a dependence on the density (Różańska et al. 2008).
Computations for higher densities show only one dip in AMD, but the amount of material in the absorber produces much higher normalization of the modeled AMD than that observed. It is difficult to say if the disappearance of this dip is connected with a switch in radiative cooling because it is valid in photoionization models of different densities. The line cooling may also be important. To confirm this result, the different SED should be considered, and we plan to explore this problem in future work.

The overall normalization of the AMD does not change much for densities up to $10^8 \text{ cm}^{-3}$, but the normalization of dips is different. Dips are deeper for lower incident densities of the absorber. The depths of the two dips were the main criteria used in our comparison of the modeled and the observed AMD presented below in Section 4.2.

In Figure 5, we show the dependence of the AMD structure on the initial ionization parameter at the irradiated side of the absorber, $\xi_0$. It can be seen that the location of the instability region remains at the same ionization range inside the absorber. The difference is only in the normalization of the dips.

There is no difference in AMD from the clouds of the same density affected by various luminosities if we assume the same ionization parameter. This is obvious due to the fact that for the same product of $\xi n_H$, the same energy flux $L/R^2$ is illuminating the absorber.

We also investigated the effect of different total column densities of the cloud on AMD. It is shown in Figure 6 and Figure 7 for the number densities $n_0 = 10^8 \text{ cm}^{-3}$ and $n_0 = 10^9 \text{ cm}^{-3}$, respectively, at the illuminated side of the absorber. As we can see from the Figure 6, absorbers at lower total column densities do not give two dips in AMD. Also, their overall normalization is lower by about half the order of magnitude. If the total column density is higher than $10^{22} \text{ cm}^{-2}$, the AMD always has two dips. The AMD ends at a lower ionization parameter for the higher total column density of the constant pressure cloud. As seen in Figure 7, when the column density is substantial, the further increase of this parameter does not change the distribution of AMD dips. This result is consistent with the conclusion made by Stern et al. (2014).

4.2. Comparison with Observations

The direct comparison of an observed AMD with the modeled one is quite hard. This is because, for the given source, we only observe from several to several of tenths of absorption lines. Each line puts a point on AMD as described in the beginning of Section 4. Note, that in the case of computed models, a few thousands of lines are included; therefore, AMD has many more points.

To date, observed AMD are found from individual observations of several objects. The general behavior of AMD in the case of five Sy1 galaxies was given by Behar (2009). All of those five galaxies (NGC 3783, NGC 5548, MCG-6-30-15, NGC 3516, NGC 7469, IRAS 13349+2438) reveal one dip in AMD located more or less in the same place between $\log \xi = 0.8$–2. The dip is not explained by the RPC model presented in this paper. Additionally, those objects are rather Sy1 galaxies with different SED than Mrk 509. The
The illuminating SED has the strong influence on AMD. For Sy 1.5 galaxy Mrk 509, AMD reveals two dips as shown by Detmers et al. (2011).

The comparison between the observed AMD for Mrk 509 (Detmers et al. 2011) and our constant pressure model computed with realistic SED input taken from current multi-wavelength studies (K11) is shown in Figure 8, where observations are given by the black histogram, and red triangles describe our model. Our calculations show the distribution of the ionization parameter much more densely. Furthermore, our column density presented in the figure by red triangles is the realistic column density, with radiation transmitted through all zones in the sequence, instead of transmission through a collection of independent zones, as in data modeling by Detmers et al. (2011), as given above by Equation (5). The lower panel of Figure 8 shows absolute values of AMD normalization. It is obvious that modeled normalization is an order of magnitude higher than the observed one in the stable zones. In the upper panel, we rescale the normalization to show that dips are fully reconstructed by our model for the given incident density and ionization parameter. We argue here, that the difference in the normalization occurs, since observed lines are saturated. Therefore, the derived ionic column densities from observations using thin slabs give only lower limits, and, in reality, can be one order of magnitude higher. To check our prediction, we have to use saturated models to fit the data. They are not very common in the literature.

There are few values of AMD normalization of several objects reported in the recent papers, both from observation and modeling. Summarizing, the agreement in the overall shape of the modeled and observed AMD dependence on the ionization parameter is very encouraging, but the normalization of the measured and modeled AMD remains an issue. The observed AMD normalization of Mrk 509 corresponding to the ionization parameter $\xi = 8 \times 10^5$ erg cm s$^{-1}$ is $\sim 10^{31}$ cm$^{-2}$ (Detmers et al. 2011), less, by a factor of $\sim 30$, than the AMD normalization from our best-fitted constant total pressure model with TITAN ($\sim 3 \times 10^{22}$ cm$^{-2}$). The AMD modeled by Stern et al. (2014) within the frame of their RPC model were shown to be fairly universal, only weakly dependent on the model parameters, and the obtained normalization values were $\sim 1.1 \times 10^{22}$ cm$^{-2}$. Measurements of AMD in six other objects (Behar 2009) implied values of the order of $\sim 4 \times 10^{21}$ cm$^{-2}$. Thus modeled values of AMD normalizations are frequently higher than the observed ones, and it is not clear whether the problem lies in the measurement method or in the modeling.

Nevertheless, for the first time, the AMD dips can be shown in model computations. The discontinuities in AMD distribution are in the range of the ionization parameter, log $\xi = 2–3$ and log $\xi = 3–4$. These ranges of $\xi$ correspond to the ranges of temperatures $T = (4–9) \times 10^5$ and $T = (2–5) \times 10^4$ K, presented in Figure 9 by the green solid line. This is proof that the absorbing material should be in pressure equilibrium and thin thermally unstable regions can be clearly visible. This comparison clearly shows that the warm absorber in Mrk 509 is the continuous cloud under constant total pressure.

The two dips are the result of the thermal instability operating in the irradiated medium. To show this effect, we present the structure of the main cloud parameters as the gas pressure, temperature, density, and the ionization parameter $\xi$ as the function of column density in Figure 9. We show the plot of the total cross section ($\sigma_{\text{tot}}$) versus column density in Figure 10 for the same case of cloud as in Figure 9. Two cases
of a sudden rise of the total cross section and a drop in the temperature can be clearly noticed, and we argue that they are responsible for the two dips in the observed AMD for Mrk 509. The discontinuity is not well resolved in the radiative transfer codes. As was pointed out by Róžańska & Czerny (1996), thermally unstable zones are geometrically very thin and the correct temperature profile in the transition zone can be recovered only after including the electron conduction. Neither TITAN nor CLOUDY have this option. However, the position of the discontinuity is well determined on the basis of radiative transfer only, as was shown by Czerny et al. (2009) and its extension depends on the model parameters.

Our result puts strong constrains that the warm absorber is build from the material of the density of the order of $10^8$ cm$^{-3}$. For SED observed in Mrk 509, the value of density changes the nature of the AMD. For densities smaller than $10^2$ cm$^{-3}$, we see two dips of different depth, as observed, and the best models compared to the data is for $10^3$ cm$^{-3}$. For densities of the order of $10^6$ cm$^{-3}$, one dip for the higher ionization parameter is substantially reduced. For the given SED, we were unable to converge computations for higher densities, but we plan to check it for objects from Stern et al. 2014, with different shapes of SEDs. Densities much lower than $10^4$ lead to the significant overprediction of the depth of the $\xi = 200$ feature, as seen from Figure 4. The discrepancy between the true modeled AMD normalization and the observed normalization, caused by the line saturation problems possibly broadens the acceptable density range. If indeed the stable parts of AMD are underestimated in the data, but the dips are not, the true depth of the dips should be larger than in the data. Assuming the true depth of the low $\xi$ dip equals four decades, then the densities as low as $10^6$ (but not lower) provide an acceptable solution for this part of AMD. However, the high $\xi$ dip is then not so well fitted.

We note that the RPC model presented by Stern et al. (2014) should reproduce the observed AMD dips since thermal instability is clearly seen in the constant pressure cloud presented in Figure 3 by cyan triangles. It was shown that the CLOUDY code fully reproduces thermal instabilities under different circumstances (Róžańska & Czerny 1996; Chakravorty et al. 2012). In our opinion, the lack of AMD dip in the Stern et al. (2014) RPC model is due to the final binning of the AMD used by those authors. They have used final bins of 0.25 dex in $\xi$ that are too rough to show thin, unstable zones. Several very small dips are actually present in the RPC model by Stern et al. (2014; see their Figure 2), but none of them explain observations.

5. CONCLUSIONS

We performed photoionization simulations of the warm absorber as a cloud illuminated by the energy emitted from the AGN center. Computations were done assuming total pressure, $P_{\text{gas}} + P_{\text{rad}}$, to be constant, and with the use of the TITAN code by Dumont et al. (2000).

We computed AMD for the case of Mrk 509, for which the SED is well known from the multi-wavelength long-term monitoring. We found discontinuities in AMD in the range of the ionization parameter, $\log \xi = 2.3$ and $\log \xi = 3.4$, similar to that obtained observationally by Detmers et al. (2011). Such observed discontinuity was often interpreted as the absence of ions in the thermally unstable regions (Holczer et al. 2007), which can also be seen in the cooling curve in Figure 3. These observed minima are also described as two geometrically distinct regions along the line of sight representing the high ionization region and the low ionization region (Holczer et al. 2007). Contrary to the work by Detmers et al. (2011), instead of two discrete zones, we explain AMD as a continuous absorber under constant total pressure.

Since the purpose of this paper is to reproduce the deep minima observed in the continuous distribution of the AMD, the modeled AMD is normalized to the observed one for convenience. The model requires higher values of column density to produce the structure all the way down to the low ionization parameter. As a result of this, the normalization of the modeled AMD is higher than the observed one. Nevertheless, the observed AMD are constructed with some approximations discussed in previous sections.

The model presented in this paper clearly shows that we can reproduce AMD in Mrk 509 only for the warm absorber with substantial density. We point out here, that Stern et al. (2014) did not obtain AMD dips from their RPC model since their modeled AMD was computed with binning that was too strong. The number of dips observed in AMD may put constraints on the density of the absorbing material, which is a crucial parameter needed to indicate the wind location through the relation Equation (1). Our work presents a new density diagnostic by matching the model with exactly the same dips normalization to the observed AMD. The dips strongly reflect geometrically narrow, thermally unstable regions. For higher densities, one dip disappears for a considered SED of Mrk 509. To confirm this result, and to search for a parametrization of the shape of the AMD dips in terms of the incident $n_0$, it is necessary to consider a sample of sources and a range of illuminating SEDs. We plan to investigate this issue in future work.

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