THE EFFECT OF UV/SOFT X-RAY EXCESS EMISSION ON THE WARM ABSORBER PROPERTIES OF ACTIVE GALACTIC NUCLEI—A CASE STUDY OF IRAS 13349+2438

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ABSTRACT

The ultraviolet (UV) to X-ray continuum of active galactic nuclei (AGNs) is important for maintaining the ionization and thermal balance of the warm absorbers (WAs). However, the spectra in the sensitive energy range $\sim 13.6–300$ eV are unobservable due to Galactic extinction. Moreover, many AGNs show soft X-ray excess emission of varying strength in the $0.1–2$ keV band, whose origin is still highly debated. This soft excess connects to the UV bump in the unobserved region of $13.6–300$ eV. Here, we investigate the effect of the assumed physical model for the soft excess on the flux of the unobserved part of the spectrum and its effect on the WA properties. We perform a case study using \textit{XMM-Newton} observations of the bright Seyfert 1 galaxy IRAS 13349+2438 with WA features. Two different physical models for the soft excess (blurred Compton reflection from an ionized disk and optically thick thermal Comptonization of the disk photons) predict different fluxes in the unobserved energy range. However, the current X-ray data quality does not allow us to distinguish between them using derived WA parameters. This, in turn, implies that it is difficult to determine the origin of the soft excess emission using the WA features.

Key words: galaxies: Seyfert – quasars: absorption lines – X-rays: individual (IRAS 13349+2438)

Online-only material: color figures

1. INTRODUCTION

About half of type I active galactic nuclei (AGNs) show soft X-ray absorption features due to partially ionized material along our line of sight intrinsic to the source (Nandra & Pounds 1994; Reynolds 1997; George et al. 1998; Blustin et al. 2005; Piconcelli et al. 2005). Such X-ray absorbing clouds were first detected by Halpern (1984) using \textit{Einstein} data and have been named partially ionized absorbers or “warm absorbers.” The availability of high resolution grating X-ray spectra with \textit{XMM-Newton} and \textit{Chandra} in the last decade enormously improved our knowledge of these discrete warm absorption and warm emission features in AGN spectra.

Warm absorber (hereafter WA) clouds give rise to narrow absorption lines and edges in the spectrum, from various ionization stages of several elements (see, e.g., Kaastra et al. 2000; Kaspi et al. 2000; Blustin et al. 2005). Absorption features from H-like and He-like ions of C, N, O, Ne, and lower ionization states of Fe (including the unresolved transition array, UTA, at $\sim 0.7$ keV) are most prominent in soft X-rays. These lines and edges are sensitive to photons in the energy range of $13.6$ eV–$2$ keV, and the ionization structure of the WA clouds depends on the shape and strength of the AGN continuum in that energy range. As such, these lines serve as important diagnostics of the ionization structure and kinematics of the gas, as well as being a probe of the continuum shape.

To model these lines and edges in a dataset and determine the ionization phase (via an ionization parameter $\xi$) and column density $N_H$ of the cloud, there are a few photoionization codes in vogue, for example, CLOUDY (Ferland et al. 1998), XSTAR (Kallman et al. 2004), etc. These codes require the ionizing continuum from the source, the cloud density, and the cloud metallicity as inputs, among other parameters, to generate a grid in $\xi$ and $N_H$. The ionizing continuum plays a very important role in determining the parameters of the cloud.

However, it is not always easy to obtain an accurate estimate of the ionizing continuum as emitted by the central engine and as seen by the WA. Due to Galactic neutral absorption, a portion of the ionizing continuum ($13.6–300$ eV) becomes unobservable. This is the region where the two most important parts of an AGN spectral energy distribution (SED) join: the Big Blue Bump (BBB) and the soft X-ray excess (SE). The BBB (peaking at $\sim 1–30$ eV) is believed to originate in the accretion disk, as thermal multi-temperature blackbody emission (Shakura & Sunyaev 1973). The SE, on the other hand, is excess emission at energies $<2$ keV over a power law extending to high energies. Until now, there has been no consensus on the physical origin of the SE and it can be well described by many prevalent models such as single or multiple blackbodies, a high temperature disk blackbody, optically thick thermal Comptonization, blurred reflection from partially ionized disk, etc. (see, e.g., Ross & Fabian 2005; Done et al. 2012). The different models used to describe the SE can predict different fluxes when extrapolated to the unobserved portion of the SED; the photons from this part of the spectrum are particularly important for WA clouds. Therefore, a physical description of the soft excess becomes imperative to describe the broadband SED. Moreover, the energy range of the soft excess ($0.3–2$ keV) is where the WA features are mainly found. Hence, the properties of the WAs are likely to depend on the way the SE is modeled.

Nicastro et al. (1999) studied the properties of the transmitted spectra of a gas illuminated by a flat and a steep X-ray spectrum. They found that different X-ray continua produce distinctly different ionization structures in a cloud, resulting in different absorption features in the energy range $0.1–2$ keV. Mehdipour et al. (2012) investigated the effect of the uncertainties in the construction of the SED of the Seyfert 1.8 galaxy ESO 113-G010 on its WAs, as it is intrinsically obscured. The uncertainties in the infrared (IR) and the ultraviolet (UV) parts of the SED were tested and were found to affect the thermal stability of each...
phase of the detected WAs. Lee et al. (2013) studied the WAs of the source IRAS 13349+2438 using Chandra data. They have found that the presence of the UV bump in the SED creates an increased number of stable phases in the stability curves and thereby favors a continuous distribution of ionization states in pressure equilibrium.

In this paper, we use different physical models describing the observed X-ray and UV data and predict the fluxes in the unobserved part of the continuum (13.6–300 eV). Furthermore, we investigate the effect of different continua on the WA properties, using a case study of an XMM-Newton observation of a bright Seyfert 1 galaxy IRAS 13349+2438, known to show strong WA features (Sako et al. 2001). We also investigate how the different shapes of the UV and soft X-ray continua affect the WA properties of the source. We furthermore carry out an extensive stability curve analysis for the different SEDs.

This paper is organized as follows. Section 2 deals with the different ionizing continua and their effects on the X-ray spectrum. Section 3 deals with the case study of IRAS 13349+2438 and describes the X-ray observations and the modeling of continuum and WA absorbers. This section also describes the construction of an appropriate ionizing continuum for IRAS 13349+2438 and investigates the effect of different ionizing continua on the observed WA properties and the stability curve analysis. Section 4 discusses the results followed by conclusions in Section 5. Throughout this work, we have used the cosmological parameters \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.27, \) and \( \Omega_\Lambda = 0.73 \) to calculate distance.

2. IONIZING CONTINUUM AND THE WARM ABSORBERS

The level of ionization in a WA cloud can be characterized by the ionization parameter \( \xi = L/nr^2 \), where \( L \) is the ionizing luminosity between 1 and 1000 Ryd, \( n \) is the hydrogen number density, and \( r \) is the distance between the ionizing source and the illuminated face of the cloud (Tarter et al. 1969). This parameter is defined for hydrogen at the cloud surface facing the ionizing radiation. The ionization structure of the cloud, on the other hand, determined by the relative ion abundances in the photoionized gas, depends on the shape of the incident spectrum. Clouds having the same ionization parameter \( \xi \) can show different absorption features when illuminated by different SEDs. Nicastro et al. (1999) found that the steep sloped narrow-line Seyfert 1s (NLSy1s) lack the presence of strong absorption edges of oxygen and other elements, whereas the flat sloped Seyfert 1 galaxies show a strong presence of \( \text{K}\alpha \) and \( \text{K}\beta \) resonance absorption lines from H-like and He-like ions of C, O, Ne, etc. The continuum strength in soft X-rays therefore plays a crucial role in determining the nature of the ionization structure of the WA cloud. This has important implications for the extent of ionization in WA clouds, as the photoelectric absorption cross sections for various elements are generally higher at lower energies above their K edges. Thus, a continuum with strong extreme UV and SE emission will produce more ionization compared with a flat continuum with strong hard X-rays. To demonstrate these effects, we created WA models for four different ionizing continua with varying UV and SE emission. The choice of these continua are driven by the case study we perform on the source IRAS13349+2438 in later sections. The four ionizing continua are as follows.

1. NLSy1 continuum. This continuum is typical of Seyfert 1 galaxies and consists of an X-ray power law (photon index \( \Gamma \sim 2 \), SE below 2 keV described as a blackbody \( kT_{BB} \sim 85 \text{ eV} \), and a multicolor accretion disk blackbody (BBB) characterized by an inner disk boundary temperature \( kT_m \sim 4 \text{ eV} \). This is the UV–X-ray continuum obtained from XMM-Newton observation of IRAS 13349+2438 (see Section 3.3) and the BBB as characterized by Lee et al. (2013) (see Section 3.5).

2. NLSy1 continuum without the BBB.

3. NLSy1 continuum without the SE.

4. NLSy1 continuum without the BBB and the SE.

Continua 2, 3, and 4 are generated to investigate the effects of various parts of the ionizing continuum on the WA clouds.

The above four ionizing continua were used to create WA models using the photoionization code CLOUDY (version 08.00; Ferland et al. 1998), which uses an extensive atomic database to predict the absorption and emission spectrum through and from a cloud. The clouds are assumed to have a uniform spherical distribution around the central source and are photoionized by the source. The geometry of the cloud is spherical but we approximate it to a plane parallel slab by making the distance of the cloud from the central source very large compared with the thickness of the cloud. CLOUDY performs the simulations by dividing a cloud into thin concentric shells referred to as zones. The thickness of the zones are chosen to be small enough such that the physical conditions across them are nearly constant. For each zone, the simulations are carried out by simultaneously solving the equations that account for ionization and thermal balance. The model predicts the absorption and emission from such clouds in thermal and ionization equilibrium. Following Porter et al. (2006), we created WA models for each of the four continua described above.

To see how the warm absorption features of these four WA models affect a spectrum, we have generated a power-law spectrum with \( \Gamma = 2 \) in the energy range 0.1–10 keV modified by the four WA models with the same column \( N_H = 10^{22} \text{ cm}^{-2} \) and the same ionization parameter \( \xi = 10 \text{ erg cm}^{-1} \text{ s}^{-1} \). This was done using the XSPEC (Arnaud 1996) spectral fitting package, where we have used a dummy response matrix to generate the fake data. Figure 1 (left panel) shows the full NLSy1 ionizing continuum in solid black along with the three different constituents of the ionizing continuum: the BBB, the SE, and the power law with a cut-off. The right panel of Figure 1 shows the absorption features of the WA clouds corresponding to the four SEDs as described above. We see that ionizing continua with different shapes can produce clouds with different absorption features for the same ionization parameter.

This is physically understandable. For example, a continuum with a strong BBB will remove most of the electrons from the atoms in the cloud capable of absorbing in the UV. On the other hand, a continuum with a strong SE will remove all the electrons capable of absorbing in the soft X-rays from their shells. So, a cloud illuminated by a strong SE is almost “transparent” in the soft X-rays as it has no further electrons left to absorb the X-rays, as we find in curve 2 in the right panel of Figure 1. To demonstrate these effects, we performed a case study of the WA properties of the bright NLSy1 IRAS 13349+2438 and discuss the effect of different parts of the ionizing continuum on the WA properties.
Figure 1. Left: the black solid line is the NLSy1 ionizing continuum as defined in Section 2. The red dashed line, the green dotted line, and the blue dashed-dotted line show the three individual components of the continuum: the BBB, the SE, and the power law with a cut-off, respectively. Right: the absorption features of a W A cloud illuminated by four ionizing continua, as described in Section 2 for the same ionization parameter ($\xi = 10\ erg\ cm\ s^{-1}$) and column density ($N_H = 10^{22}\ cm^{-2}$) in the energy band of 0.3–10 keV. The curves 1, 2, 3, and 4 denote the absorption from W A clouds illuminated by the four ionizing continua, NLSy1, NLSY1 without BBB, NLSy1 without the SE, and NLSy1 without the SE and the BBB. (A color version of this figure is available in the online journal.)

Figure 2. Top and the middle panels are 0.2–2 keV and 2–10 keV background subtracted lightcurves, respectively, of the source IRAS 13349+2438, for the EPIC-pn data of the XMM-Newton observation from 2000. The bottom panel is hardness ratio, which is seen to be constant during the observation. The last 15 ks of the observation were not used for spectral analysis due to high particle background flaring.

3. A CASE STUDY OF IRAS 13349+2438

IRAS 13349+2438 is a nearby ($z = 0.107$) bright radio quiet NLSy1 with a high bolometric luminosity ($\geq 10^{46}\ erg\ s^{-1}$). Previous X-ray studies have found the presence of strong WA, SE, and a steep power-law spectrum with $\Gamma \approx 2.2$ (Longinotti et al. 2003). This is the source in which the Fe UTA absorption features were detected by Sako et al. (2001) for the first time. A multiwavelength study of this source by Lee et al. (2013) revealed the presence of multiple components of UV and X-ray WAs. IRAS 13349+2438 has been observed by XMM-Newton on two occasions in 2000 and once in 2006. In the first observation in 2000, the X-ray spectrum showed the presence of a strong soft excess and WA features (Sako et al. 2001). Figure 2 shows the hardness ratio along with the lightcurves in the soft and the hard bands. We find that the spectral shape did not vary during the observation. For these reasons, we have chosen the source for our study.

3.1. Observation and Data Reduction

We used archival XMM-Newton data (id: 0096010101) obtained from the observation on 2000 June 20 for a total exposure of 45 ks. The EPIC-pn and metal oxide semi-conductor (MOS) cameras were operated in the small window mode using the thin filter. The data were processed using the scientific analysis system (SAS) version 12 and the latest calibration database, as available on 2012 March 3.

The EPIC data were filtered using the standard filtering criterion, which was also applied to the particle background. We recovered a net EPIC-pn exposure of $\sim 30$ ks in the EPIC-pn data, which is similar to that obtained by Longinotti et al. (2003). We checked the photon pile up using the SAS task epatplot and found that there was no noticeable pile up in either the EPIC-pn or the MOS data. We quote results based on the EPIC-pn data due to their higher signal to noise compared with the MOS data. We used the good X-ray events (FLAG = 0, pattern = 0). To extract the source spectrum, we used a circular region 45 arcsec radius centered on the centroid of the source. We extracted the background spectrum from appropriate nearby circular regions free of sources. We created the ancillary response file and the redistribution matrix file using the SAS tasks arfgen and rmfgen. We reprocessed the Reflecting Grating Spectrometer (RGS) data using the SAS task rgsproc and the optical monitor (OM) data using the SAS task omichain. The OM, EPIC, and RGS cameras simultaneously observed IRAS 13349+2438 in the UVW2 filter. We obtained the source flux at 2120 Å from the data and corrected it for Galactic extinction following Schlafly & Finkbeiner (2011) and Schlegel et al. (1998). We calculated the monochromatic flux at 2120 Å from the AGN to be $3.4 \times 10^{-15}\ erg\ cm^{-2}\ s^{-1}\ Å^{-1}$.

3.2. X-Ray Spectral Analysis

We begin with the spectral analysis of the broadband (0.3–10 keV) EPIC-pn spectral data. The data were grouped with a minimum of 20 counts per energy bin, allowing 5 energy
The best-fit $\chi^2$ parameters. The best-fit edge energy is 7 keV. The fit to the spectrum in the 2–10 keV band yielded a power-law slope $\Gamma = 1.96^{+0.08}_{-0.09}$, which is similar to that obtained by Longinotti et al. (2003). There is possibly a very weak narrow Fe Kα line and an Fe K absorption edge. We fit the Fe Kα emission line with a narrow Gaussian and the fit improved by only $\Delta \chi^2 = -4$ for two extra parameters from $\chi^2$/dof = 127/125 ~ 1.02, where dof stands for degrees of freedom. The Fe K edge was fit using an edge model in ISIS. The fit improved by $\Delta \chi^2 = -28$ for two extra parameters. The best-fit edge energy is 7.48^{+0.12}_{-0.18} \text{keV}$ and the maximum optical depth $\tau = 0.44 \pm 0.22$, similar to that found by Longinotti et al. (2003). The statistical improvement according to an F-test upon addition of this component is >99.9%. However, the best-fit $\chi^2$/dof = 99/123 suggests that the data may be over-modeled in this energy band.

We extrapolated the model to the softer part of the spectrum and found a prominent soft excess that was well described by a blackbody with a best-fit temperature of $kT_{BB} = 85 \pm 2 \text{eV}$ in the energy range 0.3–10 keV, which is again similar to that found by Longinotti et al. (2003). In Figure 3, the left panel shows clear residuals of absorption features in the soft X-ray band, which are mainly the signatures of absorption features. We used CLOUDY models to fit these absorption features.

### 3.3. Constraining the Broadband UV to X-Ray Continuum

The WA features in the X-rays consist of a number of absorption lines and edges of varying strengths and are usually unresolved and blended. In such cases, inferring X-ray continua from moderate resolution X-ray spectra requires appropriate physical models of the WA cloud. However, creating such a model requires the knowledge of the ionizing continuum seen by the WA. This is somewhat of a circular problem. We determine the continuum in the 0.3–10 keV band in the following way: we first use a generic AGN continuum to generate the CLOUDY WA table models. We use these WA models to fit the 0.3–10 keV EPIC-pn and the RGS data jointly with the X-ray continuum (Section 3.4). The BBB is then derived following Lee et al. (2013) (Section 3.5). Finally, we extrapolate the BBB and the X-ray continuum to the unobserved energy range of 13.6–300 eV and obtain the appropriate SED for the source. This SED is then used to create the WA table model and we obtain the best-fit WA and continuum parameters from the joint fit of the EPIC-pn and RGS data.

### 3.4. The X-Ray Continuum

In the first step, we use the AGN continuum given by Korista et al. (1997) to generate the WA table models in CLOUDY. The Kirk Korista continuum is given by

$$f_v = \nu^{\alpha_v} \exp(-h\nu/kT_{BB}) \exp\left(-kT_{IR}/h\nu\right) + \eta \nu^{(1-\Gamma)}.$$  

This consists of a power law in the 1 eV–100 keV band and another steeper power law in the UV whose upper exponential cut-off is parameterized by a temperature $T_{BB}$ and a lower IR cut-off $T_{IR}$. We used a typical Seyfert 1 X-ray power-law slope of $\Gamma = 2$, a UV bump blackbody temperature of $T_{BB} = 10^8 \text{K}$ peaking at $\sim 10 \text{eV}$, and $\alpha_{\nu} = -1.2$. The UV spectral slope was assumed to be $\alpha_{\nu} = -0.5$ (Elvis et al. 1994). The CLOUDY table model was built using the methods described in Porter et al. (2006). We varied $\log(\xi/\text{erg cm s}^{-1})$ from $-2$ to $4$ and $\log(N_H/\text{cm}^{-2})$ from $19$ to $24$ and created a multiplicative table model for the warm absorption. The cloud was assumed to have solar metallicity. A hydrogen density of $n_H \sim 10^6 \text{cm}^{-3}$ was assumed as the properties of the WA clouds are practically volume density independent in the range $\sim 10^2$–$10^{12} \text{cm}^{-3}$ (Netzer 1996). The table model was subsequently imported to the ISIS package and was used to obtain the best-fit 0.3–10 keV continuum parameters by carrying out a joint fit with the EPIC-pn and the RGS data. The best-fit continuum parameters are power-law slope $\Gamma = 2$ and bbbody $kT_{BB} = 85 \text{eV}$. Two ionization states of WAs were detected with best-fit parameters for the lower ionization state of $\log \xi = 1.50$ and $N_{H}^{WA} = 2 \times 10^{21} \text{cm}^{-2}$ and log $\xi = 2.25$ and $N_{H}^{WA} = 2 \times 10^{21} \text{cm}^{-2}$ for the higher ionization state. We report the best-fit continuum and the WA parameters in Table 1.

### 3.5. Characterizing the Big Blue Bump

The BBB in AGNs is primarily thought to arise from an optically thick but geometrically thin accretion disk following Shakura & Sunyaev (1973). We used the diskbb model (Makishima et al. 1986) in ISIS to define the shape of the BBB, which requires the black hole mass and distance to the source for the normalization to be determined. We characterized the UV bump following Lee et al. (2013). They derived the diskbb parameters for the same source from the optical–UV data points.

### Table 1

| Model Components | Parameters | Kirk Korista WA Model $^{a,b,c}$ | Appropriate WA Model $^{a,b,c}$ |
|------------------|------------|--------------------------------|----------------------------------|
| wabs             | $N_H \times 10^{20}$ (cm$^{-2}$) (fixed) | 1.1(f) | 1.1(f) |
| WA               | $\log(N_{H}^{WA} / \text{cm}^{-2})$ | $21.58^{+0.10}_{-0.07}$ | $21.33^{+0.09}_{-0.04}$ |
| (CLOUDY)         | $\log(\xi/\text{erg cm s}^{-1})$ | $1.50^{+0.08}_{-0.07}$ | $1.75^{+0.13}_{-0.09}$ |
| Outflow velocity | $960^{+480}_{-450}$ | $960^{+450}_{-450}$ |
| WA               | $\log(N_{H}^{WA} / \text{cm}^{-2})$ | $21.31^{+0.30}_{-0.16}$ | $21.36^{+0.23}_{-0.25}$ |
| (CLOUDY)         | $\log(\xi/\text{erg cm s}^{-1})$ | $2.25^{+0.13}_{-0.09}$ | $3.24^{+0.22}_{-0.16}$ |
| Outflow velocity | $1170^{+900}_{-600}$ | $1200^{+900}_{-600}$ |
| bbbody           | $kT_{BB}$ (eV) | $85^{+1}_{-2}$ | $87^{+1}_{-2}$ |
|                  | Norm        | $(12 \pm 2)^{f}$ | $(12 \pm 2)^{f}$ |
|                  | (power law) | $(90 \pm 20)^{f}$ | $(90 \pm 20)^{f}$ |
| Gaussian         | Line E (rest/keV) | $(0.16 \pm 0.13)^{f}$ | $(0.16 \pm 1.3)^{f}$ |
|                  | $\sigma$ (eV) | $6.4 \pm 0.007$ | $6.4 \pm 0.005$ |
|                  | Energy (keV) | $7.48 \pm 0.12$ | $7.48 \pm 0.12$ |
|                  | $\tau$      | $0.44 \pm 0.22$ | $0.40 \pm 0.22$ |
| C/dof            | $5940^{+5139}_{-5139}$ | $5935^{+5139}_{-5139}$ |
| $\chi^2$/dof    | (EPIC-pn fit only) | $213/181$ | $214/181$ |

### Notes.

$^a$ WA table model generated using the Kirk Korista continuum.

$^b$ WA table model generated using the appropriate continuum with the SE modeled with bbbody. See Section 3.6.

$^c$ (f) signifies frozen parameters.

$^{d}$ The outflow velocity of the WA with respect to the systemic velocity, expressed in km s$^{-1}$.

$^{e}$ These quantities are in units of 10$^{-5}$. 

log($N_H/\text{cm}^{-2}$) from 19 to 24 and created a multiplicative table model for the warm absorption. The cloud was assumed to have solar metallicity. A hydrogen density of $n_H \sim 10^6 \text{cm}^{-3}$ was assumed as the properties of the WA clouds are practically volume density independent in the range $\sim 10^2$–$10^{12} \text{cm}^{-3}$ (Netzer 1996). The table model was subsequently imported to the ISIS package and was used to obtain the best-fit 0.3–10 keV continuum parameters by carrying out a joint fit with the EPIC-pn and the RGS data. The best-fit continuum parameters are power-law slope $\Gamma = 2$ and bbbody $kT_{BB} = 85 \text{eV}$. Two ionization states of WAs were detected with best-fit parameters for the lower ionization state of $\log \xi = 1.50$ and $N_{H}^{WA} = 2 \times 10^{21} \text{cm}^{-2}$ and log $\xi = 2.25$ and $N_{H}^{WA} = 2 \times 10^{21} \text{cm}^{-2}$ for the higher ionization state. We report the best-fit continuum and the WA parameters in Table 1.

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obtained using the Hubble Space Telescope after correcting for the intrinsic galactic reddening. The mass of the central massive black hole of IRAS 13349+2438 is estimated to be $M_{BH} = 10^{8.75} M_\odot$, an accretion efficiency of 20% with respect to the Eddington rate is estimated, and an inner radius of $10R_s$ is hypothesized, where $R_s$ is the Schwarzschild radius. The normalization of the diskbb is obtained from these parameters and the luminosity distance of the source, which is 483 Mpc. Although the UV data used by Lee et al. (2013) were not obtained at the same time as the XMM-Newton observation, we are working with their fluxes in a similar manner as those obtained by us using the OM UVW1 filter.

3.6. The UV to X-Ray Continuum and the Warm Absorber Properties

We now develop a model ionizing continuum as emitted by the central active engine and as seen by the WA for the UV to X-ray energy band 1 eV–10 keV. For the 0.3–10 keV band continuum, the best-fit continuum model parameters obtained from the broadband EPIC-pn and RGS data in Section 3.3 are used, while the BBB is used as described in Section 3.5. In the unobserved energy range of ~13.6–300 eV, the BBB meets the extrapolated 0.3–10 keV continuum. Thus, using the UV and X-ray observations, we derived an appropriate continuum that is most likely seen by the WA clouds in IRAS 13349+2438. Figure 4 shows this continuum as a blue dotted line.

This ionizing continuum (hereafter, the “appropriate” continuum) is used to generate the WA model in CLOUDY, which is then used to fit the EPIC-pn and RGS data simultaneously. The best-fit WA parameters obtained are $\log \xi \sim 1.75$ and $N_{WA}^{H} \sim 2 \times 10^{21} \text{ cm}^{-2}$ for the lower ionization state and $\log \xi \sim 3.25$ and $N_{WA}^{H} \sim 2 \times 10^{22} \text{ cm}^{-2}$ for the higher ionization state (see Table 1 for details). We note that both the ionization states are different from those obtained using the WA model developed using the Kirk Korista ionizing continuum, although the continuum parameters are similar.

3.7. Realistic Ionizing Continuum and Physical Models for the Soft Excess

In our attempt to create an appropriate ionizing continuum, we have used a blackbody to describe the soft excess, which, however, is only a phenomenological description and the resulting continuum may not be realistic. In the absence of observations in the 13.6–300 eV range, the best solution to derive the realistic continuum is to use physical models for the SE and the BBB. Although the nature of the SE is not clearly understood, it can be well described by two physical models: (1) optically thick thermal Comptonization (optxagnf, in the ISIS notation) and (2) blurred reflection from a partially ionized accretion disk (reflionx, in the ISIS notation).

The optxagnf model proposed by Done et al. (2012) to model the soft excess involves Comptonization of disk seed photons from a complex geometry. The AGN SEDs in the UV to X-rays can be phenomenologically described by three main emission components: (1) the disk emission in the UV; (2) the
SE emission from an optically thick, low temperature thermal Comptonizing plasma; and (3) power-law emission above 2 keV from an optically thin, high temperature Comptonizing plasma. In the optxagnf model, these three main components of the spectra are combined together assuming that they are all ultimately powered by gravitational energy released in the accretion process. The optxagnf model therefore simultaneously describes the UV as well as the X-ray spectra. However, we have only one data point in the UV from the OM UVW2 filter for the given observation, which is not sufficient to constrain the model parameters. We created a set of fake datasets (in ISIS) in the UV (1 eV–10 eV) using the measured BBB described by Lee et al. (2013, see Section 3.5). We assumed typical 5% systematic errors on the UV data points. These UV data are simultaneously fitted with the EPIC-pn data to obtain the broadband UV to X-ray statistic. The above model did not describe the data well with respect to the line of sight and we tie those two parameters as 1.0. Since they arise from the same disk, we also assume that they have the same Fe abundance and same inclination angle with respect to the line of sight and we tie those two parameters as well. With the addition of this component, the fit improved to $\chi^2$/dof = 201/171, which is acceptable. No further reflection component was necessary. This X-ray continuum, along with the BBB in the UV (described in Section 3.5), were used to create the broadband SED that was used to generate the WA table models corresponding to the reflionx model. We used those WA models to fit the X-ray data. The EPIC-pn and the RGS data were simultaneously fit with wabs × WA1 × WA2 × (powerlaw + kdblur(reflionx)+kdblur(2)(reflionx2)+reflionx). Table 3 (Column 3) enumerates the best-fit parameters obtained in the fit. Figure 4 shows the three different ionizing continua derived when we used the different models to describe the soft excess. We find that the WA parameters obtained for different soft-excess models used are similar within errors (see Table 2). Hereafter, these two continua will be referred to as the “realistic continua.”

### 3.8. Effect of Various Continuum Components on the Warm Absorber Models

We constructed three new ionizing continua to investigate the individual effects of the SE and the BBB by removing these components alternately from the appropriate ionizing continuum generated earlier (Section 3.6). First, we removed the diskbb component to obtain the NLSy1 continuum without the BBB and created the WA model. Next, we created another WA model using the NLSy1 continuum without the SE. Finally, we removed both the SE and the BBB from the NLSy1 continuum and created a WA model. The continua used are shown in Figure 1. We used these WA models based on different ionizing continua to fit the absorption features in the EPIC-pn and RGS data. For each case, we obtained a lower and higher ionization state with different ionization parameters. These are listed in Table 4.

### 3.9. Stability Curve Analysis

In the WA temperature range $10^4$–$10^6.5$ K, photoionization is the main heating agent. Radiative recombination and line emission are primarily responsible for cooling the gas. The WA is assumed to be in ionization and thermal equilibrium where the above physical processes balance each other. The stability curve, which is a plot of temperature $T$ against density $n_e/n_H$ ($\xi/T$), is an effective tool that is often used to study the stability properties of WAs. Every point on this curve represents a possible equilibrium state of the gas (Krolik et al. 1981; Krolik & Kriss 1995; Reynolds & Fabian 1995; Komossa & Meurschweinchen 2000; Komossa & Mathur 2001; Kroongold et al. 2003; Netzer et al. 2003; Kroongold et al. 2005a, 2005b; Chakravorty et al. 2009, 2012). A point on a portion of the curve with positive slope corresponds to a state of stable thermal equilibrium because any small change in temperature will be countered by the physical processes to leave its physical conditions unaltered.
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Table 3
The Best-fit Parameters for the Simultaneous Fit of the EPIC-pn and RGS Data When the Soft Excess was Modeled Using Physical Models

| Model Components | Parameters | Model 1<sup>a,b</sup> | Model 2<sup>a,b</sup> |
|------------------|------------|------------------------|------------------------|
| wabs             | \( N_H \, (\text{cm}^{-2}) \times 10^{20} \) (fixed) | 1.1(\( f \)) | 1.1(\( f \)) |
| WA1 and WA2      | Values quoted in Table 2 | | |
| power law        | \( \Gamma \) | 2.04 ± 0.03 | ... |
|                  | Norm | (5.9 ± 2) \times 10^{-4} | ... |
| Reflionx-1       | Fe/solar | 10\(^{+0.0}_{-0.07}\) | ... |
|                  | \( \Gamma \) | 2.04 | ... |
|                  | \( \xi \) | 199\(^{+13}_{-14}\) | ... |
|                  | Norm | (1.43 ± 0.19) \times 10^{-6} | ... |
| Kdblur1          | Index | 9.58\(^{+0.50}_{-0.41}\) | ... |
|                  | \( R_{\text{in}}(r_g) \) | 1.23\(^{+0.07}_{-0.06}\) | ... |
|                  | \( R_{\text{out}}(r_g) \) | 13.2\(^{+0.5}_{-0.2}\) | ... |
|                  | Inclination (deg) | 37\(^{+1}_{-1}\) | ... |
| Reflionx-2       | Fe/solar | 10 (tied) | ... |
|                  | \( \Gamma \) | 2.04 | ... |
|                  | \( \xi \) | 60\(^{+21}_{-8}\) | ... |
|                  | Norm | (4.0\(^{+1.0}_{-1.0}\)) \times 10^{-7} | ... |
| Kdblur2          | Index | 3.55\(^{+0.12}_{-0.15}\) | ... |
|                  | \( R_{\text{in}}(r_g) \) | 13.2 (tied) | ... |
|                  | \( R_{\text{out}}(r_g) \) | 400(\( f \)) | ... |
|                  | Inclination (deg) | 37 (tied) | ... |
| Reflionx-3       | Fe/solar | 0.75\(^{+0.41}_{-0.18}\) | ... |
|                  | \( \Gamma \) | 2.04 | ... |
|                  | \( \xi \) | 139\(^{+28}_{-26}\) | ... |
|                  | Norm | 7.26\(^{+4.20}_{-2.20}\) \times 10^{-8} | ... |
| optxagnf         | Norm | ... | 1(\( f \)) |
|                  | log\((L/L_{\text{EDD}})\) | ... | -0.755\(^{+0.003}_{-0.004}\) |
|                  | \( kT_e \) (keV) | ... | 0.101\(^{+0.04}_{-0.02}\) |
|                  | \( \tau \) | ... | 68\(^{+5}_{-6}\) |
|                  | \( \Gamma \) | ... | 1.99 ± 0.02 |
|                  | \( f_{\text{pl}} \) | ... | 0.51 ± 0.02 |
|                  | \( r_{\text{cor}}(r_g) \) | ... | 10 ± 2 |
| Gaussian         | Norm | ... | 6.7\(^{+2.2}_{-2.0}\) \times 10^{-7} |
|                  | Line E (rest)(keV) | ... | 6.4 ± 0.005 |
|                  | \( \sigma \) (eV) | ... | 0.001(\( f \)) |
| edge             | Energy (keV) | ... | 7.48 ± 0.20 |
|                  | \( \tau \) | ... | 0.46 ± 0.22 |
| \( C/dof \)     | 5927/5139 | 5930/5139 |
| \( \chi^2/dof \) | (EPIC-pn fit only) | 201/171 | 223/176 |

Notes.
<sup>a</sup> Model 1 = \text{wabs} + \text{WA1} + \text{WA2} + \text{edge} + (\text{powerlaw} + \text{kdblur(Reflion)} + \text{kdblur2(Reflion2)}). Model 2 = \text{wabs} + \text{WA1} + \text{WA2} + \text{edge} + (\text{optxagnf} + \text{Gaussian}).

\( (f) \) stands for frozen parameters.

unchanged. However, if an absorber lies at a position on the curve with negative slope, then any small change in temperature will result in runaway heating or cooling until the properties of the gas adjust to reach a stable configuration at higher or lower temperatures.

The stability curve for a given continuum is generated using CLOUDY by stepping through different values of the ionization parameter and calculating the corresponding equilibrium temperature of the cloud.

The left panel of Figure 5 shows the stability curves for the Kirk Korista continuum and the three other continua developed for the source (the SE modeled with \text{bbody}, \text{optxagnf}, and \text{reflion}). The Kirk Korista continuum stability curve (solid black line) shows distinct regions of stable phases (positive
these ionizing continua (see Table 2) are all thermally stable. The WA components predicted by fitting the table models of distribution of temperature and pressure for the absorbing gas. Mostly stable gas. Such curves correspond to a continuous of Figure 5, we compare the stability curves derived using ones for producing stable states of the WAs. In the right panel to the fact that the realistic ionizing continua are the preferred Thus, for IRAS13349+2438, the stability curve analysis points represented by the dashed green curve, the dotted blue curve, and the dashed-dotted red curve, respectively. The corresponding best-fit WA models are denoted by the red points.

(A color version of this figure is available in the online journal.)

Figure 5. Left: the stability curves for the Kirk Korista continuum (solid black line) and for three other SEDs described in Sections 3.6 and 3.7 where the SE is described by three different models (bbody, optxagnf, reflionx). The filled circles are the two components of the best-fit WA models for the respective continua. The WA components for the Kirk Korista continuum lie on the unstable part of the stability curve, but the WA components for the realistic continua lie on the stable parts. Right: the stability curves for the test continuum where certain components of an AGN ionizing continuum have been switched off, as discussed in Section 3.8 and Table 4. The stability curve for the ionizing continuum where the BBB is switched off, the SE is switched off, and both the SE and the BBB are switched off are represented by the dashed green curve, the dotted blue curve, and the dashed-dotted red curve, respectively. The corresponding best-fit WA models are denoted by the red points.

Table 4

| WA Component | Parameters | Model 1a | Model 2a | Model 3a |
|--------------|------------|----------|----------|----------|
| 1. log\(\nu_{WA}/\text{cm}^{-2}\) | 21.33\(\pm\)0.09 | 21.36\(\pm\)0.12 | 21.38\(\pm\)0.12 |
| log(\(\xi/\text{erg cm s}^{-1}\)) | 0.99\(\pm\)0.06 | 2.29\(\pm\)0.09 | 1.30\(\pm\)0.1 |
| 2. log\(N_{H}/\text{cm}^{-2}\) | 21.49\(\pm\)0.11 | 21.44\(\pm\)0.12 | 21.44\(\pm\)0.12 |
| log(\(\xi/\text{erg cm s}^{-1}\)) | 2.50\(\pm\)0.12 | 3.30\(\pm\)0.14 | 2.36\(\pm\)0.14 |
| C/dof | 5935/5139 | 5932/5139 | 5932/5139 |

Note. a Model 1 stands for the BBB switched off from the NLSy1 SED, as described in Section 2. Model 2 stands for the SE switched off. Model 3 stands for the BBB, as well as the SE, switched off.

4. DISCUSSION

We have shown that ionizing continua with different shapes can result in different ionization structures for a cloud even if they have the same ionization parameter \(\xi\) (see Figure 1; see also Nicastro et al. 1999; Reynolds & Fabian 1995). The 13.6–300 eV range in the UV to X-ray SEDs of AGNs is not accessible to us with our current state-of-the-art instruments. This is the energy range where photons are important for maintaining the ionization balance of the WA clouds. Several authors in the past have used different techniques to overcome this difficulty. In many cases, authors have used a single power-law ionizing continuum with a typical photon index of \(\Gamma \sim 1.5\)–2 in the UV to X-ray band (e.g., Reynolds & Fabian 1995; Matt et al. 2011; Lobban et al. 2011; Winter et al. 2012). In some cases, a power law connecting the two observed fluxes at 2 keV and 2500 Å, characterized by a slope \(\alpha_{OX}\), has been used for the unobserved part of the continuum (see, e.g., Netzer 1993; Longinotti et al. 2008; Nucita et al. 2010). This method ignores the presence of the SE, which we have seen is important in maintaining the ionization balance of the WA. Some authors have modeled the UV data with a power law and joined the last UV data point, for instance, 2120 Å from the OM telescope, with the lowest available X-ray data point (~300 eV) to create the broadband SED (see, for e.g., Gupta et al. 2013; Krongold et al. 2005b; Yaqoob et al. 2003). Dewangan et al. (2007) treated the SE as

slopes) separated by intermediate unstable phases (negative slopes). Such a stability curve would predict discrete phases of WAs that may be in pressure equilibrium with each other. This is because \(\xi/T\) is essentially the ratio between radiation pressure and gas pressure if the distance from the ionizing source is the same for the different clouds of ionized gas. The solid blue points on the curve show the two components of the WA that were derived from fitting the data. We find that both components of the WA fall in nearly unstable regions of the stability curve. On the other hand, the curve due to the two realistic continua (optxagnf and reflionx) predict mostly stable gas. Such curves correspond to a continuous distribution of temperature and pressure for the absorbing gas. The WA components predicted by fitting the table models of these ionizing continua (see Table 2) are all thermally stable. Thus, for IRAS13349+2438, the stability curve analysis points to the fact that the realistic ionizing continua are the preferred ones for producing stable states of the WAs. In the right panel of Figure 5, we compare the stability curves derived using the appropriate SED for IRAS 13349+2438 (see Section 3.6) with stability curves obtained by dropping the BBB and the SE components, respectively, from the SED. We have shown in the figure in red circles the WA components predicted by fitting the data with the WA models created using the respective continua. We find that the BBB, as well as the SE components, are crucial in establishing a largely stable curve and ensuring that the WA components fall in the stable parts of the curve.
disk blackbody emission and used a UV power law to construct the ionizing continuum.

To constrain the spectral shape in the unobserved energy range, the best one can do is use physical models to describe the BBB and the SE using the observed data and extrapolate them into the unobserved range. Lee et al. (2013) modeled the SE in the *Chandra* HETG spectrum of IRAS 13349+2438 with a physical model, nthcomp, which involves Comptonization of seed photons from an accretion disk by a thermal gas of electrons, and extrapolated the resulting continuum below 100 eV where it meets the BBB in the unobserved energy range. In the present case study of the NLSy1 galaxy IRAS 13349+2438 using *XMM-Newton* data, we followed a similar procedure, but we have used two additional physical models to describe the SE—the intrinsic disk thermal Comptonization (optxagnf) and the blurred reflection from an accretion disk (reflionx). The optxagnf model is similar to the nthcomp model for the SE but it also produces the BBB and the hard X-ray power law self consistently. We find that these different models, when extrapolated to the unobserved energy range, predict different fluxes (see Figure 4). The model optxagnf, which simultaneously describes the X-ray and the UV data, predicts more flux in the 10–100 eV range compared with the bbody model. The reflionx model, which required a separate disk bbody model to characterize the BBB, predicts more flux in the energy range 20–100 eV. The predicted fluxes in the 13.6–300 eV range for the three cases optxagnf, reflionx, and bbody are $2.5 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1}$, $1.5 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1}$, and $1.4 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1}$, respectively. However, the X-ray data we are working with cannot distinguish between the WA models created by the two physical SEDs. We find that the two different models lead to similar best-fit WA parameters (see Table 2). The implication of these results is that the observed WA properties cannot be used to distinguish between the currently available physical models for the SE.

The ambiguity in the derived WA ionization parameters for a source due to the uncertainty in the SED means that we cannot determine the “unique” ionization parameter for a given cloud for a given dataset. For example, when we use the appropriate SED (described in Section 3.6) for the source IRAS 13349+2438, we obtained the best-fit ionization parameters for the WA clouds $\log \bar{\xi} \sim 1.75$ and $\log \bar{\xi} \sim 3.25$, whereas the WA models developed using the SE model when the BBB is switched off from the NLSy1 SED yielded completely different best-fit WA ionization parameters ($\log \bar{\xi} \sim 0.99$ and $\log \bar{\xi} \sim 2.50$). Sako et al. (2001) studied the same observation of the source IRAS 13349+2438 and obtained two phase WA clouds. After modeling the continuum, they applied the absorption components of individual ions H- and H-like C, N, O, Ne, and Fe xvii–xv, where each ion was treated as a separate component in the spectral fit. From the observed distribution of the charge states of these ions, they derived the average ionization parameters using XSTAR: for the lower ionization state, $\log \bar{\xi} \leq 1.0$, $N_{H}^{WA} \sim 10^{21} \text{ cm}^{-2}$, and outflow velocity is $v \sim 400 \text{ km s}^{-1}$; for the higher ionization state, $2.0 \leq \log \bar{\xi} \leq 2.5$, $N_{H}^{WA} \sim 10^{22} \text{ cm}^{-2}$, and outflow velocity is $v \sim 0 \text{ km s}^{-1}$. We found that both ionization parameters are consistent with those derived by us when we used the WA models based on the appropriate continuum without the BBB (see Table 4). The ionization parameters obtained by us using the WA model based on realistic continuum are higher than those obtained by Sako et al. (2001), however, they are similar to those obtained by Lee et al. (2013). Mehdipour et al. (2012) found different best-fit WA parameters when they used different SEDs to generate the WA models. We found that the outflow velocity and the column density parameters for the WA models generated using different SEDs are statistically similar, which was also found by Mehdipour et al. (2012).

The structure of the WA clouds is still elusive. There is as of yet no consensus whether the clouds exist in clumpy discrete phases or as a continuous plasma. In two of the high quality X-ray spectra of NGC 3783 (Netzer et al. 2003) and NGC 5548 (Steenbrugge et al. 2003), the data required three ionization phases. It is not clear if these AGNs really host discrete WA phases as the current data seem to suggest or if the number of WA phases increases with increasing data quality, indicating a continuous distribution of WA clouds. Various studies have, however, pointed toward a growing consensus on the discrete phases of WAs (Blustin et al. 2003; Smith et al. 2008; Ricci et al. 2010; Mehdipour et al. 2010; Ebro et al. 2011). The stability curves provide a way to distinguish between the two scenarios. For the source IRAS 13349+2438, we found that the effect of the BBB and the SE on the stability curves enables stable WA phases over a wide range of $\xi/T$ valves (see also Reynolds & Fabian 1995; Fabian et al. 1986). Therefore, the continuum might influence the formation of specific phases. Fabian et al. (1986) showed that the two phase, discrete WA model for the source Mrk 841 is not valid since the stability curves exhibited more stable regions when they added a SE component to an existing simple power-law model in the X-ray continuum. We find that the stability curve generated using the Kirk Korista continuum, which has no SE, has discrete stable and unstable phases. The best-fit WA parameters for this continuum lie on the unstable portions of the curve. This may point toward a picture where the WA clouds exist in clumpy phases. On the contrary, the stability curves generated using the realistic SED for IRAS13349+2438 with the BBB and SE (Figure 5, left panel) have only stable phases and the best-fit WA parameters lie always on the stable parts of the curves. This points to a continuous distribution of WA clouds as the available phase space in $\xi/T$ is largely stable. This can impact our understanding of the formation of the WAs (Reynolds & Fabian 1995). Lee et al. (2013) also point out that the presence of a strong UV and SE component creates more stable phases in the stability curve. Holczer et al. (2007) had used only the X-ray continuum for the same source to generate stability curves and found unstable phases, which are not present when the SED by Lee et al. (2013) is used. Therefore, we find that the stability curves generated using the realistic continua prefer a continuous distribution of WA ionization states. However, as a caveat, we may consider that the detection of two discrete WA components in the stable region of the S curve may not always imply that there is a continuous distribution of ionization states in the absorber along the line of sight to this target. The S curves built using the “realistic” continua show largely stable portions and allow for a continuous distribution of ionization states and yet we detect only two discrete states. The fact that we see only two components with very different ionization degrees and nothing in between may argue against the continuous-flow distribution of ionization states.

5. CONCLUSION

In this paper, we investigated the effects of the shape of the ionizing continuum on the WA properties. The main results are as follows.
1. Ionizing continua with different shapes create different ionization structures in WA clouds for the same ionization parameter and column density of the cloud. The best-fit WA parameters obtained using WA models generated with different input ionizing continua for the Seyfert 1 galaxy IRAS 13349+2438 are different.

2. The determination of the accurate shape of the ionizing continuum therefore becomes imperative for generating the WA models, which is, however, not possible due to the Galactic extinction in the range 13.6–300 eV. The only viable technique is to characterize the BBB and the SE with physical models and extrapolate them into the unobserved region of theSED.

3. We developed realistic continua based on multiwavelength observations that consist of the SE and power-law emission in the X-rays and the BBB in the UV. We found that the different physical models for SE (blurred Compton reflection and optically thick thermal Comptonization) predict different fluxes in the unobserved energy range, but the current X-ray data quality does not allow us to distinguish between them using the derived WA parameters.

4. The extent of stable regions in the stability curves is large for the realistic continuum, which possibly indicates a continuous distribution of WA clouds for this source.

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