ABSORPTION MEASURE DISTRIBUTION OF THE OUTFLOW IN IRAS 13349+2438: DIRECT OBSERVATION OF THERMAL INSTABILITY?

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ABSTRACT

We analyze the Chandra X-ray spectrum, obtained with the HETGS grating spectrometer, of IRAS 13349+2438, which has one of the richest absorption spectra of a quasar outflow. Absorption from almost all charge states of Fe is detected. This allows for a detailed reconstruction of the absorption measure distribution (AMD), which we define as the continuous distribution of column density as a function of ionization parameter. We find a double-peaked AMD for IRAS 13349+2438, with a total (ionized) column density of \( N_\text{H} = (1.2 \pm 0.3) \times 10^{22} \text{ cm}^{-2} \), assuming solar iron abundance. For comparison, we perform a similar analysis on the well-studied HETGS spectrum of NGC 3783. Both sources feature a deep minimum in column density that is consistent with no absorption from gas at temperatures of \( 4.5 < \log T < 5 \) (K). We interpret the minima as observational evidence for thermal instability in this temperature regime.

Subject headings: galaxies: active — galaxies: individual (IRAS 13349+2438, NGC 3783) — line: formation — techniques: spectroscopic — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

The X-ray spectra of many active galactic nuclei (AGNs) viewed directly toward the central source (e.g., Seyfert 1 galaxies) show the continuum flux absorbed by numerous absorption lines produced by ionized gas. The lines are generally shifted to shorter wavelengths, indicating an outflowing wind. It is not clear whether this wind can also be associated with the line-of-sight material responsible for the optical reddening of these sources. To that end, the outflow would have to entail neutral gas or dust grains along with the highly ionized wind. It is still controversial as to whether the winds are significant for the AGN central engine or for the host galaxy in terms of mass, energy, and momentum. It is possible that extreme outflows may even play a central role in cosmological feedback and in the metal enrichment of the intergalactic medium (IGM). In order to address these open questions, it is important to develop reliable techniques to probe the winds and to perform accurate measurements of their physical properties.

The X-ray band is advantageous for AGN outflow studies, not only because most of the outflow appears to be highly ionized, but also since the X-ray band comprises detectable absorption lines from the full range of charge states, from neutral up to hydrogen-like. Moreover, in most cases an X-ray spectrum features several lines from a single ion, which helps one to deduce ionic column densities from saturated absorption lines. The detection of many charge states of a single element is key to plasma diagnostics, as it allows one to model the distribution of ionization and to measure the total column density independent of assumptions regarding the relative element abundances. For this purpose, Fe ions are particularly useful, as they form over several orders of magnitude of the ionization parameter, defined (e.g., Kallman & Krolik 1995) by

\[
\xi = \frac{L}{n_H r^2},
\]

where \( L \) is the ionizing luminosity between 1 and 1000 ryd, \( n_H \) denotes the hydrogen number density, and \( r \) is the distance of the absorber from the ionizing source. Once the distribution of the ionization is known for one element, the relative abundances of other elements can be measured by comparison. For the absolute abundances of metals with respect to hydrogen, one still needs to utilize UV spectra, as the energies of atomic transitions in hydrogen are too low to be observed in X-rays. Highly ionized K- and L-shell ions (1–2 and 3–10 electrons, respectively) of Fe appear regularly in astrophysical X-ray sources, either in emission or in absorption. The lower charge states of Fe (11–26 electrons) feature strong inner shell absorption lines in the soft X-ray band (Behar et al. 2001b). Each ion can produce dozens of overlapping lines forming unresolved transition arrays (UTAs). Interestingly, IRAS 13349+2438 was the first source in which Fe M-shell UTAs were observed (Sako et al. 2001). The majority of works on the X-ray spectra of AGN outflows fit the data with a gradually increasing number of iso-\( \xi \) absorption components until the fit is satisfactory (e.g., Kaspi et al. 2001; Kaastra et al. 2002; Netzer et al. 2003). For high-quality spectra, two or three ionization components produce a good fit. In this work, we employ a more fundamental method that tries to reconstruct the actual distribution of the column density in the plasma as a continuous function of \( \xi \). We call this distribution the absorption measure distribution (AMD). The present method is similar in principle to that tested by Steenbrugge et al. (2005) and by Costantini et al. (2007), who assumed a power-law distribution. However, here we fit for the AMD directly from the measured ionic column densities, making no a priori assumptions regarding its shape.

IRAS 13349+2438 is a bright type 1 quasar \( (L > 10^{46} \text{ erg s}^{-1}) \) at a redshift of \( z = 0.10764 \) (Kim et al. 1995). Optical and infrared observations by Wills et al. (1992) have suggested absorption of the central source by dust. X-ray observations with ROSAT (Brandt et al. 1996) and ASCA (Brandt et al. 1997) did not find a significant column density of cold material, but suggested the presence of ionized gas along the line of sight, perhaps with embedded dust grains. Siebert et al. (1999) restated the difficulty of explaining the optical and X-ray observations with the same

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absorber. The line-resolved RGS (Reflection Grating Spectrometer) on board *XMM-Newton* spectrum of IRAS 13349+2438 measured by Sako et al. (2001) revealed broad (FWHM $\approx 1400 \pm 300$ km s$^{-1}$) absorption lines of many ions. Two distinct ionization components were determined at log $\xi$ $\approx 0$ and at log $\xi$ $\approx 2$–2.5, where $\xi$ is in units (erg cm s$^{-1}$). The low- and high-$\xi$ components were found to have column densities of a few times $10^{21}$ cm$^{-2}$ and a few times $10^{22}$ cm$^{-2}$, respectively. The good agreement between the low-$\xi$ column density and that deduced from the optical reddening (Wills et al. 1992) led Sako et al. (2001) to conjecture that the low-$\xi$ absorber might be responsible also for the optical reddening. In this paper, we revisit the ionized absorber of IRAS 13349+2438, using a long exposure with the High Energy Transmission Grating (HETGS) spectrometer on board *Chandra* that was performed 3 yr and 9 months after the *XMM-Newton* observation. The spectral resolution of the HETGS is much better than that of the RGS, and the long exposure compensates for its inferior effective area.

2. DATA REDUCTION

IRAS 13349+2438 was observed by the *Chandra* HETGS on 2004 February 22–26 for a total exposure time of 300 ks. All observations were reduced from the *Chandra* archive using the standard pipeline software (CIAO version 3.2.1). The total number of counts in the first (plus and minus) orders between 2 and 20 Å is 22836 for the MEG (medium-energy grating) and 9542 for the HEG (high-energy grating). No background subtraction was required, as the background level was negligible. The post-pipeline procedure is similar to the method reported in Kaspi et al. (2001). Flux spectra were obtained by dividing the count spectra by the effective area curves produced by the standard CIAO tool. Positive and negative first-order data of both the spectra by the effective area curves produced by the standard pipeline procedure is similar to the method reported in Kaspi et al. (2001). The data were rebinned to 36 m bins to improve the statistics of the spectra with minimal compromise of the spectral resolution, as the MEG instrumental line-spread function is approximately 23 m broad (FWHM).

3. SPECTRAL MODEL

Variations of approximately 25% on timescales of 20 ks were observed during the 300 ks exposure of IRAS 13349+2438. Due to this low level of variability, and since we are interested in the overall properties of the ionized absorber, henceforth we use only the combined MEG and HEG full 300 ks spectrum. The present fitting procedure follows our ion-by-ion fitting method (Behar et al. 2001a, 2003; Holczer et al. 2005). First we fit for the broadband continuum. Subsequently we fit the absorption features using template ionic spectra that include all of the absorption lines and photoelectric edges of each ion, but that vary with the broadening (so-called turbulent) velocity and the ionic column density.

3.1. Continuum Parameters

The continuum spectrum of IRAS 13349+2438 can be characterized by a high-energy power law and a blackbody that rises at lower energies. The present best-fit power-law parameters are a photon index of $\Gamma = 1.9$ with a total flux in the 5–35 Å range of $2.8 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$, to be compared with the values of $\Gamma = 2.2$ and a flux of $2.4 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ obtained by Sako et al. (2001). The current blackbody has a temperature of $kT = 105$ eV and a 5–35 Å flux of $7.8 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$, compared to the values of $kT = 100$ eV and $4.4 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ obtained by Sako et al. (2001). The continuum applied by Brandt et al. (1997) to the *ASCA* data produced a flux in the 2–10 keV range of $5.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, compared to the present value of $3.6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. The continuum applied by Brandt et al. (1996) to the *ROSAT* data produced a flux in the 0.1–2.5 keV range of $1.2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ compared to the present value of $1.7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. In short, the continuum measured here with *Chandra* is within $\sim$50% of all previous observations. In particular, the continuum model parameters are fairly similar to those of Sako et al. (2001). In Figure 1 we present a direct comparison of the two grating spectra from these two observations, showing their overall similarity. It can be seen that the hard X-ray flux is almost identical, while there is some increase in the soft flux. This change is reflected in the small difference between the two models in the blackbody normalization parameters. One might note that the depth of the O K-shell edges is also different between observations. This is discussed in more detail in § 4.1.

3.2. The Ionized Absorber

The spectrum $I_0(\nu)$ around an atomic absorption line $i \rightarrow j$ can be represented by

$$I_0(\nu) = I_0(\nu) \exp \left[ -N_{\text{ion}}\sigma_0(\nu) \right],$$

where $I_0(\nu)$ represents the continuum intensity and $\sigma_0(\nu)$ denotes the line absorption cross section for photoexcitation (in units of cm$^2$) from ground level $i$ to level $j$, if all ions are essentially in the ground level, and $N_{\text{ion}}$ is the total ionic column density toward the source (in units of cm$^{-2}$). The photoexcitation cross section is given by

$$\sigma_0(\nu) = \frac{\pi e^2}{m_e c} f_0(\nu) \phi(\nu),$$

where $f_0$ denotes the absorption oscillator strength and $\phi(\nu)$ represents the Voigt profile due to the convolution of natural (Lorentzian) and Doppler (Gaussian) line broadening. The Doppler broadening consists of thermal and turbulent motion, but in AGN outflows, the turbulent broadening appears to totally dominate
the Doppler broadening. Transition wavelengths, natural widths, and oscillator strengths were calculated using the Hebrew University Lawrence Livermore Atomic Code (HULLAC; Bar-Shalom et al. 2001). More recent and improved atomic data for the Fe M-shell ions were incorporated from Gu et al. (2006).

The Doppler broadening can be typically characterized by a turbulent velocity $v_{\text{turb}}$ although for very high resolution UV spectra of AGN outflows, this approximation has been shown to be inadequate and thus velocity-dependent partial covering effects need to be taken into account (Arav et al. 1999). Due to the limited resolution, the present HETGS spectrum of IRAS 13349+2438 does not warrant a more sophisticated analysis than the $v_{\text{turb}}$ approximation. Indeed, a turbulent velocity of $v_{\text{turb}} = 640$ km s$^{-1}$, corresponding to a FWHM of $\sim 1500$ km s$^{-1}$, provides a good fit to the strongest absorption lines in the spectrum, as demonstrated in Figure 2 for the Fe$^{16}$ absorption line at 15.01 Å. This specific absorption line is shown because it has a high oscillator strength of 2.3 and it is relatively unblended. The value of $v_{\text{turb}} = 640$ km s$^{-1}$ is consistent with that quoted by Sako et al. (2001).

Since the absorbing gas is outflowing, the absorption lines are slightly blueshifted with respect to the AGN rest frame. The current best-fit outflow velocity is $-300 \pm 50$ km s$^{-1}$. Errors correspond to $\Delta \chi^2 = 1$. Sako et al. (2001), on the other hand, found from the RGS spectrum two velocity components: high- and low-ionization components with velocities of $+20^{+380}_{-200}$ km s$^{-1}$ and $-420^{+190}_{-190}$ km s$^{-1}$, respectively. We find that a single outflow velocity of $-300 \pm 50$ km s$^{-1}$ actually provides a better fit to the HETGS spectrum. In Figure 2, the centroid of the Fe$^{16}$ line can be seen to be offset from the zero-velocity position by at least 6 σ ($= 50$ km s$^{-1}$). Sako et al. (2001) ascribed this line to the high-ionization component, with $v_{\text{out}} = +20^{+380}_{-200}$ km s$^{-1}$. The $-300$ km s$^{-1}$ blueshift (obtained by fitting all absorption lines in the spectrum simultaneously) clearly provides a better fit to the profile of this specific line. We ascribe the potential discrepancy with Sako et al. (2001) to the superior spectral resolution of the present HETGS measurement and to the large errors on the velocities of Sako et al. (2001). If anything, the data in Figure 2 hint at an even higher velocity for this specific line, which might suggest that there is some scatter in velocity between the different ions. However, this effect is too weak for us to measure even with HETGS, and henceforth we assume a uniform outflow velocity of $-300 \pm 50$ km s$^{-1}$.

Our model includes all of the important lines of all ion species that can absorb in the wave band observed by HETGS. In the present spectrum of IRAS 13349+2438, we find evidence for the following ions: N$^{16}$, all charge states of O, Ne$^{6}$–Ne$^{9}$, Mg$^{14}$–Mg$^{11}$, Na$^{10}$, Si$^{5}$–Si$^{13}$, 21 ions of Fe, and Ni$^{18}$. We also include the K-shell photoelectric edges for all these ions, although their effect here is largely negligible. When fitting the data, each ionic column density is treated as a free parameter. A preliminary fit is obtained using a custom-made Monte Carlo fitting method applied to the entire spectrum. Subsequently, the final fit is obtained for individual ionic column densities in a more controlled manner, which ensures that the fit of the leading lines is not compromised. The best-fit model for the present spectrum of IRAS 13349+2438 is shown in Figure 3. It can be seen that the Si, Mg, Ne, and Fe L-shell lines are reproduced fairly well by the model. However, in the Fe M-shell region between 15.0 and 17.5 Å, the spectrum is rather noisy and it is difficult to identify individual ions. For these ions, only rough estimates of the column densities can be obtained. Note that some lines could be saturated; e.g., the leading lines of O$^{16}$ and O$^{17}$. In these cases, the higher order lines with lower oscillator strengths are crucial for obtaining reliable $N_{\text{ion}}$ values.

4. IONIC COLUMN DENSITIES

4.1. Results

The best-fit ionic column densities are listed in Table 1. For the most part, the column densities of the Fe, Si, and Mg ions are on the order of $10^{16}$–$10^{17}$ cm$^{-2}$. The column densities of N$^{16}$ and the Ne ions exceed $10^{17}$ cm$^{-2}$, while those of the O ions reach $\sim 10^{18}$ cm$^{-2}$. Comparing these results with those of Sako et al. (2001), we find that the Fe M-shell column densities are consistent. The present column densities for the O K-shell ions are much higher, while those of the Fe L-shell ions are much lower than those of Sako et al. (2001). In order to understand this discrepancy, we went back to the RGS spectrum and compared both data and models with the present spectrum. We conclude that the O K-shell column densities indeed did vary between observations. This can be seen even in our Figure 1, where the features of O$^{16}$ and O$^{17}$, marked by labels, are clearly deeper in the present spectrum, even though the soft excess continuum is higher. Conversely, for all non-oxygen ions, we find that the present ionic column densities obtained from fitting the HETGS spectrum actually reproduce the RGS spectrum fairly well. Other than O, we have no good explanation for the discrepancies with Sako et al. (2001).

Interestingly, we find a relatively high column density of neutral Fe that may not be part of the outflow, as manifested by the L$_{\alpha}$ absorption UTA at 17.53 Å (see Fig. 3). If we use the solar Fe/H abundance ratio (Asplund et al. 2005), we obtain a neutral gas column density of $N_{\text{H}} \sim 3.5 \times 10^{21}$ cm$^{-2}$, much higher than the Galactic column of $N_{\text{H}} \sim 10^{20}$ cm$^{-2}$. This may indicate the presence of neutral gas or dust in the host galaxy, reminiscent of the Wills et al. (1992) finding.

4.2. Error Determination

The column density errors quoted in Table 1 were calculated by keeping an individual ionic column density fixed while performing a minimum $\chi^2$ fit with all other parameters and then requiring that $\Delta \chi^2 = 1$ for variations of that individual ionic
column density, while all other parameters remain fixed. The more statistically rigorous method would be to require $\Delta \chi^2 = 1$ following a refit of the data. However, since we supplement $\chi^2$ fitting with a more controlled manual fit to the strongest lines, leading to a best fit that is not strictly the $\chi^2$ minimum, the method that involves automatic $\chi^2$ minimization is inapplicable here. Nevertheless, our simpler method gives reliable upper limits to the errors. For the cases in which the relative error was less than 10%, we assume an error of 10%. The reason is that even for the most prominent lines, we do not trust the column density to better than

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**Fig. 3.—** Chandra HETGS spectrum of IRAS 13349+2438, corrected for cosmological redshift ($z = 0.10764$). The thick black line shows the best-fit model, in which a blueshift velocity of $-300$ km s$^{-1}$ was applied to all ions. Ions responsible for the strongest lines and blends are marked above the data. [See the electronic edition of the Journal for a color version of this figure.]
We use geometrically averaged rather than arithmetically averaged errors, since the geometrical average gives an average in order of magnitude between the two errors, which is the more appropriate value to be applied as a symmetrical error. For the full AMD analysis (presented in § 5.1), we use the true asymmetrical errors in the manner explained below.

5. ABSORPTION MEASURE DISTRIBUTION

5.1. Method

The large range of ionization states present in the absorber strongly suggests that the absorption arises from gas that is distributed over a wide range of ionization parameters. The total hydrogen column density \( N_H \) along the line of sight can therefore be expressed as an integral over its distribution in \( \log \xi \). We call this continuous distribution the absorption measure distribution (by analogy to the emission measure distribution in emission-line spectra):

\[
AMD = dN_H/d(\log \xi),
\]

\[
N_H = \int AMD \, d(\log \xi). \tag{5}
\]

The relation between the ion column densities \( N_{\text{ion}} \) and the AMD is then expressed as

\[
N_{\text{ion}} = A_{\text{ion}} \int \frac{dN_H}{d(\log \xi)} f_{\text{ion}}(\log \xi) \, d(\log \xi), \tag{7}
\]

where \( N_{\text{ion}} \) is the measured ion column density, \( A_{\text{ion}} \) is the element abundance with respect to hydrogen (assumed to be constant throughout the absorber), and \( f_{\text{ion}}(\log \xi) \) is the fractional ion abundance with respect to the total abundance of its element. Here we aim at recovering the AMD for IRAS 13349+2438.

As an initial approximation to be relaxed later, let us assume that each ion forms exclusively at the ionization parameter \( \xi_{\text{max}} \) where its fractional abundance peaks. Furthermore, if solar abundances \( A_{Z} \) are assumed, the equivalent hydrogen column density can be calculated separately from each ion using the relation

\[
N_H \approx \frac{N_{\text{ion}}}{f_{\text{ion}}(\xi_{\text{max}})A_{Z}}, \tag{8}
\]

and can be placed at the position of \( \xi_{\text{max}} \) on an \( N_H(\log \xi) \) plot. For this we employed the XSTAR code (Kallman & Krolik 1995) version 2.1kn3 to calculate \( f_{\text{ion}}(\log \xi) \) using the continuum derived in § 3.1, extrapolated to the range of 1–1000 ryd. The results for IRAS 13349+2438, using solar abundances from Asplund et al. (2005), are presented in Figure 4. The ions pertaining to each element in the figure are connected by straight lines to guide the eye. The fact that the connecting lines of Fe, Si, Mg, O, and Ne largely overlap in this plot implies that the relative abundances of these elements do not deviate much from the solar values. On the other hand, the relative abundances of \( N_{\text{Na}} \) and \( N_{\text{Ne}} \) appear to be significantly above solar, although there is only one Na and one Ne ion to show this result. The errors in Figure 4 are those propagated from the \( N_{\text{ion}} \) symmetrical uncertainties, as explained in the previous section (§ 4.2).

The distribution presented in Figure 4 is only a first approximation for the actual AMD. For the real AMD, we need to find a distribution \( dN_H/d(\log \xi) \) that, after integration (eq. [7]), will produce all of the measured ionic column densities (Table 1). In fitting the AMD, one must take into account the full dependence of \( f_{\text{ion}} \) on \( \xi \). We assume that all charge states see the same ionizing spectrum. This is justified by the absence of significant bound-free absorption edges in the spectrum. All elements

### Table 1: Best-Fit Column Densities

| Ion   | HETGS Column Density \((10^{19} \text{ cm}^{-2})\) | RGS Column Density \((10^{19} \text{ cm}^{-2})\) |
|-------|---------------------------------|---------------------------------|
| \(\text{N}^0\) | \(45^{+21}_{-19}\) | \(13^{+8}_{-8}\) |
| \(\text{O}^3\) | \(30^{+10}_{-0}\) | \(3^{+4}_{-4}\) |
| \(\text{O}^{10}\) | \(40^{+5}_{-10}\) | \(9^{+2}_{-2}\) |
| \(\text{O}^{14}\) | \(15^{+20}_{-0}\) | \(3.7^{+2.7}_{-2.7}\) |
| \(\text{O}^{15}\) | \(78^{+10}_{-0}\) | \(9.5^{+4.7}_{-4.7}\) |
| \(\text{Ne}^8\) | \(140^{+5}_{-10}\) | \(22^{+35}_{-35}\) |
| \(\text{Ne}^{10}\) | \(5^{+20}_{-0}\) | \(120^{+50}_{-50}\) |
| \(\text{Ne}^{11}\) | \(16^{+12}_{-12}\) | \(49^{+100}_{-100}\) |
| \(\text{Na}^{10}\) | \(7^{+10}_{-10}\) | \(5^{+10}_{-10}\) |
| \(\text{Mg}^{14}\) | \(2^{+10}_{-0}\) | \(5^{+10}_{-10}\) |
| \(\text{Mg}^{15}\) | \(8^{+10}_{-0}\) | \(5^{+10}_{-10}\) |
| \(\text{Mg}^{16}\) | \(6^{+10}_{-0}\) | \(5^{+10}_{-10}\) |
| \(\text{Mg}^{18}\) | \(4^{+10}_{-0}\) | \(5^{+10}_{-10}\) |
| \(\text{Mg}^{19}\) | \(2^{+10}_{-0}\) | \(5^{+10}_{-10}\) |
| \(\text{Mg}^{20}\) | \(5^{+10}_{-0}\) | \(5^{+10}_{-10}\) |
| \(\text{Mg}^{21}\) | \(1^{+10}_{-0}\) | \(5^{+10}_{-10}\) |
| \(\text{Si}^{5}\) | \(15^{+20}_{-20}\) | \(5^{+10}_{-10}\) |
| \(\text{Si}^{6}\) | \(5^{+10}_{-0}\) | \(5^{+10}_{-10}\) |
| \(\text{Si}^{7}\) | \(7^{+10}_{-10}\) | \(5^{+10}_{-10}\) |
| \(\text{Si}^{8}\) | \(7^{+10}_{-10}\) | \(5^{+10}_{-10}\) |
| \(\text{Si}^{9}\) | \(9^{+10}_{-10}\) | \(5^{+10}_{-10}\) |
| \(\text{Si}^{10}\) | \(9^{+10}_{-10}\) | \(5^{+10}_{-10}\) |
| \(\text{Si}^{11}\) | \(9^{+10}_{-10}\) | \(5^{+10}_{-10}\) |
| \(\text{Si}^{12}\) | \(9^{+10}_{-10}\) | \(5^{+10}_{-10}\) |
| \(\text{Si}^{13}\) | \(9^{+10}_{-10}\) | \(5^{+10}_{-10}\) |
| \(\text{Fe}^{16}\) | \(2^{+10}_{-0}\) | \(5^{+10}_{-10}\) |
| \(\text{Fe}^{17}\) | \(2^{+10}_{-0}\) | \(5^{+10}_{-10}\) |
| \(\text{Fe}^{18}\) | \(1.5^{+1.5}_{-1.5}\) | \(5^{+10}_{-10}\) |
| \(\text{Fe}^{19}\) | \(1.5^{+1.5}_{-1.5}\) | \(5^{+10}_{-10}\) |
| \(\text{Fe}^{20}\) | \(1.5^{+1.5}_{-1.5}\) | \(5^{+10}_{-10}\) |
| \(\text{Fe}^{21}\) | \(1.5^{+1.5}_{-1.5}\) | \(5^{+10}_{-10}\) |
| \(\text{Fe}^{22}\) | \(1.5^{+1.5}_{-1.5}\) | \(5^{+10}_{-10}\) |
| \(\text{Fe}^{23}\) | \(1.5^{+1.5}_{-1.5}\) | \(5^{+10}_{-10}\) |
| \(\text{Ni}^{14}\) | \(0.6^{+0.6}_{-0.6}\) | \(5^{+10}_{-10}\) |

Note.—Column densities are given for ions detected in the 2004 HETGS spectrum of IRAS 13349+2438 and are compared with those in the 2000 RGS observation (Sako et al. 2001).

10%. Conversely, when the relative error was more than 200%, we quote a nominal error of 200%. In these cases, we believe that the errors are not statistical.

In § 5.1 we need to use symmetrical errors. In order to get a reliable symmetrical error estimate, we introduced one more adjustment. We define a geometrically averaged error:

\[
\text{err}_{\text{symm}} = \sqrt{\text{err}_{\text{up}} \text{err}_{\text{down}}}. \tag{4}
\]
are expected to reflect the same AMD distribution, due to the assumption that they all reside in the same gas. Iron, however, has a special role, as it covers almost 5 orders of magnitude in \( \xi \), more than any other element. Nonetheless, in order to improve the AMD fit, we can use other elements as well. In order to incorporate the non-Fe ionic column densities without assuming anything about the elemental abundances, for non-Fe ions we use column density ratios. Using a reference ion for each element (the one with the smallest symmetrical errors), these ratios can be written as

\[
\frac{N_{\text{ion}}}{N_{\text{ion-ref}}} = \frac{A_z \int [dN_{\text{ion}}/d(\log \xi)] f_{\text{ion-ref}}(\log \xi) d(\log \xi)}{A_z \int [dN_{\text{ion}}/d(\log \xi)] f_{\text{ion}}(\log \xi) d(\log \xi)}.
\]  

(9)

Since there is no a priori physical argument for a specific functional form for the AMD, we choose to use a simple staircase function (Fig. 5). The main advantage of this form is the well-localized, easily calculated errors. A similar approach was used by Nordon et al. (2006) for emission.

The fit is performed with our Monte Carlo evolution program, in which the only free parameters are the values of the AMD in each \( \log \xi \) bin. The program receives starting values for each bin and then generates 5000 other AMD solutions randomly in the multidimensional region around the starting point. For each solution, the value of \( \chi^2 \) is calculated, and the lowest \( \chi^2 \) solution is subsequently considered as the new starting point. This process is repeated until \( \chi^2 \) cannot improve any more. In our tests, the program always converged to the same best-AMD solution for arbitrary starting values within 5 orders of magnitude (higher or lower) of the final result. This gives us confidence that the fit finds the global minimum. As this is an ill-defined inversion problem, the AMD binning is driven by the correlated errors. At first, we use 10 bins in the range of \( \log \xi = -1.25 \) to 3.75 (cgs), assuming that the AMD is zero elsewhere. We then combine bins so that the range and number of bins are optimized so that AMD bin values are inconsistent with zero (to within 1 \( \sigma \)), except in broad regions of \( \xi \) in which the AMD is consistently zero. The final number of bins (i.e., the AMD resolution) depends on the specific absorber and on the quality of the data, which can limit the bin size.

The AMD fit is obtained by the \( \chi^2 \) minimization technique with respect to all of the measured Fe \( N_{\text{ion}} \) values (eq. [7]) and \( N_{\text{ion}} \) ratios of at least one other element (eq. [9]). In the calculation of \( \chi^2 \), the real asymmetrical errors are used so that when the best-fit AMD overestimates an ionic column density, the upper limit error is used, and vice versa. For non-Fe ions, the same rule is applied to \( N_{\text{ion}} \), while symmetrical errors are used for \( N_{\text{ion-ref}} \) (eq. [9]).

The AMD errors are calculated in each bin, including correlations between bins. The AMD in a given bin is varied from its best-fit value, and the whole distribution is refitted. This procedure is repeated until \( \Delta \chi^2 = 1 \). The fact that changes in the AMD in one bin can be compensated by varying the AMD in other bins dominates the AMD uncertainties. This is what limits the number of bins and the AMD resolution. The AMD in neighboring, excessively narrow bins cannot be distinguished by the data; i.e., different distributions produce the measured \( N_{\text{ion}} \) values to within the errors. A meaningful quantity is the integral of the AMD up to \( \xi \) (as a function of \( \xi \)), since correlated errors cancel out during integration, which explains the small errors on the integrated column density (Fig. 5, bottom).

The next step is to estimate the element abundances relative to Fe. This is done by assuming that the other elements are distributed in \( \log \xi \) similarly to Fe, or in other words, that the shape of the AMD (e.g., Fig. 5) is manifested in the column density distribution of each and every element. This is what one would expect for a chemically uniform absorber. Indeed, the overlap
of elements in Figure 4 seems to support this assumption. In order to obtain the abundances, we used the AMD distribution by varying the AMD normalization to best fit the column densities of each ion. This single-parameter fit yields for each ion the relative abundance of each ion. This single-parameter fit yields for each ion the relative abundance of each ion. The AMD features a statistically significant minimum at 0.75 < log ξ < 1.75 (cgs), which corresponds to 4.5 < log T < 5 (K) and which was noted also by Sako et al. (2001). This minimum is a manifestation of the relatively low ion column densities observed for the ions Fe$^{11+}$–Fe$^{15+}$, as seen in Figure 4 and in Table 1.

In order to check that the observed minimum in the AMD of IRAS13349+2438 is not a result of the signal-to-noise ratio (S/N), we want to apply the same method to another ionized absorber with a wide range of ionization. The natural choice is the 900 ks HETGS spectrum of NGC 3783. We use the spectrum from Kaspi et al. (2002, their Fig. 5), and the same method described above. The results are presented in Figures 6 and 7 in the same format as for IRAS 13349+2438 (Figs. 4 and 5). The AMD of NGC 3783 was obtained using 23 ions of Fe and 4 ions of Ne. Already in Figure 6, low column densities for the Fe$^{12+}$–Fe$^{16+}$ and Si$^{9+}$–Si$^{11+}$ charge states can be seen around log ξ ≃ 1–2 (cgs). Indeed, in the staircase AMD reconstruction for NGC 3783 presented in Figure 7, we find a minimum at 0.75 < log ξ < 1.75 (cgs), which corresponds to 4.5 < log T < 5 (K). This minimum is surprisingly similar to that of IRAS 13349+2438, but is more statistically significant and thus better constrained in ξ. We note that a similar minimum has been recently observed in NGC 7469 as well (Blustin et al. 2007).

In Figures 6 and 7, we include comparisons with the two-component model of Kröndel et al. (2003) and the three-component model of Netzer et al. (2003) for the same NGC 3783 HETGS data set. The ionization components of these papers are placed on the plot according to T rather than ξ, as different models produce different relations between temperature and ξ. The bin size is set arbitrarily to Δ log ξ = 0.5 (cgs). The column density of each component in those papers then determines the area (height) of its AMD contribution in Figure 7. It can be seen that all models avoid the region of the AMD minimum between log ξ ≃ 1 and 2 (cgs). On the other hand, only the present method, which allows for a complete distribution, accounts for the full range of absorbing gas from log ξ = −1.25 to log ξ = 3.75 (cgs). We obtain a total (integrated) N$_\alpha$ value of (4.1 ± 0.7) × 10$^{22}$ cm$^{-2}$ and (2.0 ± 0.8) × 10$^{22}$ cm$^{-2}$ obtained by Netzer et al. (2003) and by Kröndel et al. (2003), respectively, of Netzer et al. (2003) and of Kröndel et al. (2003), where each component is broadened arbitrarily to Δ log ξ = 0.5 (cgs) bins. [See the electronic edition of the Journal for a color version of this figure.]
consistent with solar values. For NGC 3783, where it is at its solar value. In general we can say dance ratios are slightly above or at about their solar value. The ion detections. In both AGNs the Ne/Fe, Mg/Fe, and O/Fe abundances are slightly above or at about their solar value. The Si/Fe ratio is above solar. The S/Fe ratio can be measured only for NGC 3783, where it is at its solar value. In general we can say that in both AGNs the metal abundances are approximately consistent with solar values.

5.3. Discussion: Observing Thermal Instability

The extent to which we can describe the low-ionization region of the AMD strongly depends on the photoionization balance, which is highly uncertain at low $\xi$ for two main reasons. First, the uncertainties in the dielectronic recombination (DR) rates of the low charge states of Fe at low (photoionized) temperatures are well known to be severely underestimated in all codes, including XSTAR; see Netzer (2004) and, recently, Badnell (2006). Correcting these would shift the ionization balance at a given $\xi$ value toward lower charge states, which would result in a more compact AMD, not extending as far on the low-$\xi$ end. The other effect that could drastically change our low-$\xi$ AMD is photoionization of the low charge states by the EUV and UV continuum, which is only poorly constrained. For example, a softer continuum than we assumed here (see § 3.1) would allow for more highly ionized M-shell charge states at a given $\xi$ value. Consequently, it is important to understand that the exact position of the low-$\xi$ peak of the AMD for both IRAS 13349+2438 and NGC 3783 is only poorly constrained and will depend on the combined correction for the DR rates and for the soft continuum. Conversely, the total column density in this component, as well as the existence of a minimum in the AMD, is robust.

One explanation that comes to mind for the minimum observed in the AMDs of both IRAS 13349+2438 and NGC 3783 is thermal instability. If photoionized gas is thermally unstable at these temperatures, it would provide a natural explanation for the absence of absorption and for the low column densities of the charge states that form primarily at these temperatures. Note that our AMD binning is driven by the requirement for meaningful errors. Consequently, we cannot determine where the alleged instability occurs to better accuracy than the $\xi$ and $T$ regimes given above, as narrower bins will inevitably result in excessive AMD uncertainties. The resulting AMD distributions presented in Figures 5 and 7, along with their similar minima, are reminiscent of what is widely referred to in the literature as the two-phase models of gas in photoionization equilibrium (Krolik et al. 1981). These models have been invoked for AGNs, most importantly, to allow for the confinement of low-$T$, high-density clouds by high-$T$ diffused gas. It is important to stress that the currently derived AMD is not a model. It represents a direct measurement of the ionization structure of the absorber that is more complete and more detailed than a multiple iso-$\xi$ fit. To that end, the observed AMD minima provide direct evidence for a thermal unstable temperature region that cannot be obtained from iso-$\xi$ fits.

The observed minimum or two-phase structure can also be ascribed to two geometrically distinct regions along the line of sight, a high-ionization region and a low-ionization region, both of which have their own Gaussian-like AMDs. However, there are reasonable good reasons to believe that gas at $4.5 < \log T < 5$ (K) would be unstable, as the cooling function $\Lambda(T)$ is generally decreasing in this temperature regime (Krolik et al. 1981). In addition, the model of Netzer et al. (2003; their Fig. 12) for NGC 3783 shows that this region is marginally unstable. The model of Gonçalves et al. (2006) for NGC 3783 avoids temperature zones, which could be a result of thermal instability. Interestingly, the avoided region at $4.5 \leq \log T \leq 5$ (K) is consistent with the present measurement. However, there is another region of avoidance in that model at $5.3 \leq \log T \leq 6$ (K) that our measurement does not show. The model of Krognold et al. (2003) has a very wide unstable region at $5.3 \leq \log T \leq 7.5$ (K). However, both Netzer et al. (2003) and Krognold et al. (2003) find an absorption component in this temperature regime, as we do. As the regions of instability depend strongly on unobserved regions of the ionizing spectra, the theoretical stability analysis models have to be treated with caution.

6. Conclusions

We have analyzed the thermal and chemical structure of the ionized outflow in the quasar IRAS 13349+2438. Using a new AMD reconstruction method, we measure the distribution of column density in the outflow as a function of $\xi$. We find a double-peaked distribution with a significant minimum at $0.75 < \log \xi < 1.75$ (cgs), which corresponds to temperatures of $4.5 < \log T < 5$ (K). Using a comparison method of the AMD derived for different elements, we are able to estimate the relative chemical abundances in the outflow. We find that all of the abundances relative to Fe are more or less solar. For comparison, we applied the same analysis to the excellent-quality X-ray spectrum of NGC 3783. We find a similar minimum in the AMD and rather similar abundances, suggesting perhaps that these could be common features in AGN outflows. We believe that this minimum is due to thermal instability.

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REFERENCES

Arav, N., Becker, R. H., Laurent-Muehleisen, S. A., Gregg, M. D., White, R. L., Brotherton, M. S., & de Kool, M. 1999, ApJ, 524, 566
Asplund, M., Grevesse, N., & Sauval, J. A. 2005, in ASP Conf. Ser. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ed. T. G. Barnes III & F. N. Bash (San Francisco: ASP), 25
Badnell, N. R. 2006, ApJ, 651, L73
Bar-Shalom, A., Klapisch, M., & Oreg, J. 2001, J. Quant. Spectrosc. Radiat. Transfer, 71, 169
Behar, E., Cottam, J. C., & Kahn, S. M. 2001a, ApJ, 548, 966
Behar, E., Rasmussen, A. P., Blustin, A. J., Sako, M., Kahn, S. M., Kaastra, J. S., Branduardi-Raymont, G., & Steenbrugge, K. C. 2003, ApJ, 598, 232
Behar, E., Sako, M., & Kahn, S. M. 2001b, ApJ, 563, 497
Blustin, A. J., et al. 2007, A&A, 466, 107
Brandt, W. N., Fabian, A. C., & Pounds, K. A. 1996, MNRAS, 278, 326
Brandt, W. N., Mathur, S., Reynolds, C. S., & Elvis, M. 1997, MNRAS, 292, 407
Costantini, E., et al. 2007, A&A, 461, 121
Gonçalves, A. C., Collin, S., Dumont, A.-M., Mouchet, M., Róžańska, A., Chevallier, L., & Goosmann, R. W. 2006, A&A, 451, L23
Gu, M. F., Holezer, T., Behar, E., & Kahn, S. M. 2006, ApJ, 641, 1227
Holezer, T., Behar, E., & Kaspi, S. 2005, ApJ, 632, 788
Kaastra, J. S., Steenbrugge, K. C., Raassen, A. J. J., van der Meer, R. L. J., Brinkman, A. C., Liedahl, D. A., Behar, E., & de Rosa, A. 2002, A&A, 386, 427
Kallman, T. R., & Krolik, J. H. 1995, XSTAR: A Spectral Analysis Tool (Greenbelt: NASA Goddard Space Flight Center)
Kaspi, S., et al. 2001, ApJ, 554, 216
———. 2002, ApJ, 574, 643
Kim, D. C., Sanders, D. B., Veilleux, S., Mazzarella, J. M., & Soifer, B. T. 1995, ApJS, 98, 129
Krolik, J. H., McKee, C. F., & Tarter, C. B. 1981, ApJ, 249, 422
Krongold, Y., Nicastro, F., Brickhouse, N. S., Elvis, M., Liedahl, D. A., & Mathur, S. 2003, ApJ, 597, 832
Murphy, E. M., Lockman, F. J., Laor, A., & Elvis, M. 1996, ApJS, 105, 369
Netzer, H. 2004, ApJ, 604, 551
Netzer, H., et al. 2003, ApJ, 599, 933
Nordon, R., Behar, E., & Güdel, M. 2006, A&A, 446, 621
Sako, M., et al. 2001, A&A, 365, L168
Siebert, J., Komossa, S., & Brinkmann, W. 1999, A&A, 351, 893
Steenbrugge, K. C., et al. 2005, A&A, 432, 453
Wills, B. J., Wills, D., Evans, N. J., II, Natta, A., Thompson, K. L., Breger, M., & Siriko, M. L. 1992, ApJ, 400, 96