**CHANDRA LETGS SPECTROSCOPY OF THE QUASAR MR 2251–178**

**AND ITS WARM ABSORBER**

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**ABSTRACT**

We present an analysis of our *Chandra* Low Energy Transmission Grating Spectrometer (LETGS) observation of the quasar MR 2251–178. The warm absorber of MR 2251–178 is well described by a hydrogen column density $N_{H} \approx 2 \times 10^{21}\,\text{cm}^{-2}$ and an ionization parameter $\log(\xi) \approx 0.6$. We find in the spectrum weak evidence for narrow absorption lines from carbon and nitrogen which indicate that the ionized material is in outflow. We note changes (in time) of the absorption structure in the band 0.6–1 keV (around the unresolved transition arrays [UTAs] plus the O viii and O vi K edges) at different periods of the observation. We measure a 0.1–2 keV flux of $2.58 \times 10^{-11}\,\text{ergs cm}^{-2}\,\text{s}^{-1}$. This flux implies that the nuclear source of MR 2251–178 is in a relatively low state. No significant variability is seen in the light curve. We do not find evidence for extra cold material in the line of sight, and set an upper limit of $N_{H} \approx 1.2 \times 10^{20}\,\text{cm}^{-2}$. The X-ray spectrum does not appear to show evidence for dusty material, although an upper limit in the neutral carbon and oxygen column densities can only be set to $N_{C_{i}} \approx 2 \times 10^{19}\,\text{cm}^{-2}$ and $N_{O_{i}} \approx 9 \times 10^{19}\,\text{cm}^{-2}$, respectively.

**Subject headings:** galaxies: active — quasars: individual (MR 2251–178) — X-rays: galaxies

**Online material:** color figures

**1. INTRODUCTION**

Warm absorbers have provided deep insights into the nuclear environment of active galactic nuclei (AGNs). Halpern (1984) reported the presence of a warm absorber for the first time using the *Einstein* observation of the QSO MR 2251–178. Since then warm absorbers have been commonly found in about 50% of AGN spectra (see Komossa & Hasinger 2003; Crenshaw et al. 2003 for reviews), and their study has enriched our knowledge about the ionization and the kinematics of the gas composing these systems, which is important for understanding of the evolution of these objects, and the AGN unification picture.

In this context MR 2251–178, at $z = 0.06398$ (Bergeron et al. 1983), has been the subject of various studies, first due to its historical importance as the first quasar discovered by X-ray observations (Ricker et al. 1978), as the first warm absorber reported (Halpern 1984), and because it displays a number of outstanding characteristics. It is surrounded by a large [O iii] emission-line region, located in the outskirts of a cluster of galaxies (Bergeron et al. 1983), with a high $L_{v}/L_{\text{opt}}$ ratio. Several studies have been focused on the characterization of the absorbing material properties. Komossa (2001) fitted a warm absorber model to the *ROSAT* observation of MR 2251–178, and found a high ionization state of the absorber ($\log U \sim 0.5$) and a column density of $N_{H} \sim 10^{22.6}\,\text{cm}^{-2}$. Monier et al. (2001) reported the presence of absorption lines of N v $\lambda 1240$ and C iv $\lambda 1549$ blueshifted by a few hundreds of kilometers per second. Ganguly et al. (2001) noticed variability of the C iv $\lambda 1549$ line by taking observations from the *Hubble Space Telescope (HST)* 4 years apart, and inferred a maximum distance from the source of $\sim 2.4\,\text{kpc}$.

More recently, Kaspi et al. (2004), based on an 8.5 yr data set from *ASCA*, *BeppoSAX*, and *XMM-Newton*, established a scenario in which clouds crossing our line of sight are indicated by the presence of absorption lines from high ionization states, displaying a wide range of velocity, from 0 to $\sim 600\,\text{km s}^{-1}$.

Gibson et al. (2005) analyzed data from the High Energy Transmission Grating on board *Chandra*, and found evidence in the spectrum of MR 2251–178 of highly ionized, high-velocity ($v \sim 12,000–17,000\,\text{km s}^{-1}$) outflowing material. They report column densities similar to those of Kaspi et al. (2004), of a few times $10^{21}\,\text{cm}^{-2}$, and establish conditions for the accretion and mass-loss rates.

From the Fe xxvi $\lambda 63$ line, Gibson et al. (2005) concluded that unless the absorber covering factor is very low, the mass-loss rate is approximately an order of magnitude higher than the accretion rate that would account for the radiation power of MR 2251–178 ($\sim 0.2\,M_{\odot}\,\text{yr}^{-1}$, at 10% efficiency). This is a different conclusion from that reached by Monier et al. (2001) in the *Hubble Space Telescope (HST)* analysis of the same object, in which they established that the accretion and mass-loss rates are essentially the same. Examining this point is relevant to understanding the evolution mechanisms in the nucleus of MR 2251–178. On the other hand, the HETGS high-resolution observation also reveals the presence of emission lines coming from highly ionized species, and shows that the emitting material is not in our line of sight, opening the possibility that the absorption and the emission lines have different physical origins or that they are located at different distances from the nucleus. This phenomenon has been observed in NGC 4051 in the optical/ultraviolet band. Komossa & Fink (1997) concluded that the coronal emission lines from low ionized species of Fe ([Fe vii]–[Fe xi]) observed in the spectrum of this object have a different physical origin from the warm absorber. This is consistent with the fact that they could come from a different spatial region, namely, the warm absorber located at the nucleus and the coronal lines extended out to $\sim 150\,\text{pc}$ (Nagao et al. 2000).
Finally, dusty warm absorbers have been found in a number of AGNs (Komossa & Hasinger 2003 and references therein for a review) and are predicted to leave their mark on the X-ray spectra of AGNs, for instance, the K edges of O i and C i (Komossa & Fink 1997; Komossa & Bade 1998) and the Fe L edge (Lee et al. 1997; Komossa & Bade 1998) for the global structure of MR 2251–178.

For the first time, we search for the presence of a dusty warm absorber in MR 2251–178. Based on ROSAT data, Komossa (2001) speculated about the presence of a second, dusty warm absorber in MR 2251–178, but the data did not allow multicomponent fitting, which would have important implications for the global structure of MR 2251–178.

It is clear from this introduction that each of the previous missions and the use of more powerful spectroscopic instruments have led to new perspectives on the properties and evolution of the nuclear environment of MR 2251–178. We present an overview and an analysis of the spectrum of MR 2251–178 as it is seen with Chandra’s Low Energy Transmission Grating Spectrometer (LETGS). The spectral resolution power of the instrument allows us to confirm some previous conclusions about the ionization and kinematics of the warm absorber of MR 2251–178 and sheds new light on the evolution, ionization, and composition of this system.

Technical details on the observation and data reduction are given in § 2. Our spectral analysis is given in § 3.2. The mean properties of the warm absorber of MR 2251–178 are presented in § 3.4, with the corresponding spectral absorption lines analysis. In § 4 we offer a temporal analysis of the absorption structure around the O vii and O viii K edges. We discuss the results in § 5 and conclude in § 6. Throughout this paper, we use the following cosmological parameters: \( H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}, \Omega_M = 0.3 \), and \( \Omega_L = 0.7 \).

2. OBSERVATION AND DATA REDUCTION

We obtained a ~80 ks exposure time observation of MR 2251–178, performed with the Chandra LETGS (Brinkman et al. 2000; under the sequence number 700405 and ObsID 02966). A log of the observation is presented in Table 1. The spectrum was obtained by reducing the data with the Chandra Interactive Analysis of Observation (CIAO, ver. 3.3).1

We use the default spectral extraction region (i.e., a bow-tie–shaped region). When the LETG (Low Energy Transmission Grating) is used with the HRC-S detector (High Resolution Camera), this region comprises a central rectangle abutted to outer regions whose widths increase as the dispersion distance increases. The background region is taken from above and below the dispersed spectra. The region’s shape for both the source and the background negative and positive orders is precisely given in the file letgD1999-07-22regN0002.fits.2

Having properly extracted both the source and background spectra from each arm, we merged them, obtaining added source and background spectra. This procedure is intended to increase the signal-to-noise ratio (S/N) of the final spectrum, and throughout this work our spectral analysis is based on this co-added spectrum. The effective areas (EAs) for orders from 2 to 10 used in fitting procedures were taken from the LETG+HRC-S effective areas Web site.3 For the first order we used the corrected EA of Beuermann et al. (2006). EA orders from 1 to 10 (positive and negative orders) were summed to be used with the corresponding co-added spectrum.

The nominal LETGS wavelength range is 1.24–175 Å (0.07–10 keV). However, we restrict our spectral analysis to the range 1.24–124 Å (~0.1–10 keV). In the range ~0.07–0.09 keV the S/N ratio is low (~1.4 at ~0.09 keV), and we exclude bins in this band from our analysis. Also, we exclude bins that fall in the bands in which the gaps of the detector (HRC-S) are located (i.e., 52–56 and 62–66 Å, for the left and right gaps, respectively). Figure 1 shows the summed (positive and negative dispersion orders) background-subtracted count rate spectrum of MR 2251–178, adaptively binned to have at least 100 counts from the source per bin over the range considered in this work. It is known that an instrumental feature at ~2.08 keV, related to the mirror, could be modeled by an edge with negative optical depth.4 We model this 1r M edge of the mirror by using an edge model with the energy fixed to 2.08 keV and an optical depth equal to ~0.15. Thus, all our fits include this negative edge model. All wavelengths and energies are presented in the observed frame.

2.1. Source Extent and Light Curve

In order to search for evidence that the source has a spatial extent or for the presence of other possible X-ray sources (for example, jets) close to MR 2251–178, we take the zeroth-order image (chip 2 on HRC-S) of MR 2251–178 centered at R.A. = 22h54m05.08 \( \pm \) 0.05 s and decl. = ~17°34′55″ \( \pm \) 0.05″ (J2000.0) in a field of view of 10″ × 10″. The extent of the emission (and the 90% encircled energy; computed with the cell detect command of CIAO)5 is consistent with being inside the zone dominated by the point-spread function (PSF; for the LETGS ~1.8″). We conclude that no evidence of appreciable extent of the source is found in this observation (we also checked for angular dependence

1 At http://cxc.harvard.edu/ciao.
2 The file can be found at http://cxc.harvard.edu/cal/Letg.
3 http://cxc.harvard.edu/cal/Letg/Hrc_/QE/ea_/index.html.
4 At http://cxc.harvard.edu/ccw/proceedings/03_proc/presentations/marshall2/s001.html.
5 See http://cxc.harvard.edu/ciao3.3/download/doc/detect_manual/cell_run.html.

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**TABLE 1**

*Chandra Observation Log of MR 2251–178*

| Sequence Number | UT Start | UT End | Time (ks) |
|-----------------|----------|--------|-----------|
| 700405          | 2002 Dec 23, 16:35 | 2002 Dec 24, 14:54 | 78.5 |

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**FIG. 1**—The 0.1–10 keV LETGS spectrum of MR 2251–178 (observed frame). It is binned to have at least 100 counts from the source per bin. In red the model of a simple absorbed power law modified by two oxygen absorption edges. [See the electronic edition of the Journal for a color version of this figure.]
in the X-ray image and found that the emission of the object is symmetrically distributed.

The light curve constructed from the zeroth order of the observation is shown in Figure 2 (top). Counts are binned to 200 s bins. We find a mean value of 111 counts bin\(^{-1}\) \((\text{horizontal red line})\) without any significant variation within 1 \(\sigma\) \((\text{horizontal green lines})\). In the bottom panel we present the light curve of the background (here the green lines show \(\pm 3\) \(\sigma\)). The good time intervals are indicated by the interrupted line below the background spectrum. The meaning of intervals 1–4 is explained in §4. [See the electronic edition of the Journal for a color version of this figure.]

3. GLOBAL SPECTRAL MODELS

3.1. Flux and Luminosity \((0.1–10 \text{ keV})\)

To compute the hard and soft X-ray fluxes we fit a simple power law to the total spectrum\(^7\) absorbed only by the Galactic column density of \(N_{\text{HI}} = 2.77 \times 10^{20} \text{ cm}^{-2}\) (Lockman & Savage 1995), and we obtain a photon index of \(\Gamma_x = 1.94 \pm 0.03\) and a normalization value of \(5.64 \pm 0.08 \times 10^{-3}\) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV.

Then we integrate the unabsorbed power law\(^7\) to obtain a flux in the 0.1–2 keV band \(f_{0.1-2\text{keV}} = 2.58 \pm 0.05 \times 10^{-11} \text{ ergs cm}^{-2} \text{s}^{-1}\); and the 0.1–2 keV luminosity is \(L_{0.1-2\text{keV}} = 2.54 \times 10^{44} \text{ ergs s}^{-1}\), a factor of \(\approx 1.5\) fainter than the \textit{ROSAT}\ soft X-ray observation.

The 2–10 keV flux is \(f_{2-10\text{keV}} = 1.64 \pm 0.05 \times 10^{-11} \text{ ergs cm}^{-2} \text{s}^{-1}\); and the 2–10 keV source luminosity is \(L_{2-10\text{keV}} = 1.62 \times 10^{44} \text{ ergs s}^{-1}\). This is \(\approx 30\%\) lower than the 2–10 keV luminosity measured by Gibson et al. (2005) of \(L_{2-10\text{keV}} = 2.41 \times 10^{44} \text{ ergs s}^{-1}\) (but see footnote 5).

In our computation, 284 of the total of 321 bins included in this analysis are in the 0.1–2 keV band, so all the spectral analysis is actually driven by the soft part of the spectrum. The information contained in the 0.1–0.5 keV band is important to our conclusion that the soft X-ray flux is between \(\approx 10\%–80\%\) of the hard fluxes historically measured from the spectrum of MR 2251–178. Recently this object was observed in the hard X-ray band (14–195 keV) with the \textit{Swift} Burst Alert Telescope (BAT), with \(L_{14-195\text{keV}} = 10^{45} \text{ ergs s}^{-1}\) (Markwardt et al. 2005). Taking our best-fit power law and integrating over the 14–195 keV band, we predict a luminosity \(L_{14-195\text{keV}} = 3 \times 10^{44} \text{ ergs s}^{-1}\), a factor of a few lower than the \textit{Swift} observation. The full range \((0.1–10 \text{ keV})\) luminosity is \(L_{0.1-10\text{keV}} = 4.17 \times 10^{44} \text{ ergs s}^{-1}\). Our measured 0.1–2 keV flux allows us to conclude that MR 2251–178 is in a relatively low soft X-ray state.

3.2. Spectral Models

The rest of the spectral analysis of the present work was carried out with the Interactive Spectral Interpretation System package (ISIS, ver. 1.4,4)\(^8\) using the XSPEC modules from the \textit{heasoft} libraries.\(^9\)

MR 2251–178 is surrounded by a giant emission-line nebula with an extent of \(\approx 10–200\) kpc (e.g., Bergeron et al. 1983; Macchetto et al. 1990). Bergeron et al. (1983) estimated a column density of a few times \(10^{21} \text{ cm}^{-2}\) of the emission-line gas. They speculated about the presence of an extended neutral \(\text{H} \, \text{i}\) halo around MR 2251–178, which should be detectable in \(\text{H} \, \text{i}\) 21 cm observations or in the soft X-ray band, if it is also located along our line of sight (see also §6.1 of Komossa 2001 for further motivation). We begin our fitting procedure by searching for and placing constraints on any cold material along our line of sight to the quasar that is in excess of the Galactic absorption toward MR 2251–178.

We fit a simple power law, absorbed by a column of cold gas in the line of sight, to the X-ray spectrum of MR 2251–178. Both the power-law parameters and the column density are free parameters. The best-fit photon index and column density we obtain are \(\Gamma_x = 1.79 \pm 0.02\) and \(N_{\text{HI}} = 1.68 \pm 0.07 \times 10^{20} \text{ cm}^{-2}\), respectively. We plot in Figure 3 the best-fit absorbed power-law model along with the spectrum of MR 2251–178 in energy space. The best-fit column density is about 40\% lower than the Galactic value toward MR 2251–178 \((2.77 \times 10^{20} \text{ cm}^{-2};\) Lockman & Savage 1995). If we fix the column density to the Galactic value and refit, we obtain a slight change in the value of the photon

\(^{7}\) We also compute the flux using a two power-law model, which represents in a better way the 2–10 keV band, with deviations from the data not larger than 1\%.

\(^{8}\) At http://space.mit.edu/CXC/ISIS/index.html.

\(^{9}\) At http://heasarc.nasa.gov/docs/software/lheasoft/.
index, to $\Gamma_1 \sim 1.9$, and the fit gets worse with a change in $\Delta \chi^2 \sim 140$. Taking the upper limit of the extra cold material reported by Komossa (2001), of $\Delta N_{\text{H}} \approx 5 \times 10^{19}$ cm$^{-2}$, and including it in the column of gas, we obtain a photon index slightly steeper, and the fit gets worse if we increase the column density of the extra cold material by 1 and 2 times $N_{\text{H}}$ (see rows 3 and 4 in Table 2), increasing $\chi^2$ (compared to the model with $N_{\text{H}}$ free to vary) by $\Delta \chi^2 = 260$ and 396, respectively.

We also carefully investigate whether excess X-ray absorption, above the Galactic value, and a blackbody component could be combined to compensate each other so as to mimic a less absorbed spectrum. This case is shown graphically in Figure 3 (solid line) for the composite model [i.e., zphabs, (pl+bb)] in comparison with the absorbed power law (top panel). The best-fit intrinsic (AGN frame) extra column density has a value (given the data) consistent with zero.

We tried a final model composed of two power laws and cold absorption. The result is shown in Figure 3 (second panel from top). A steep power law ($\Gamma_1 \approx 3.5$), with the help of the cold absorption, describes relatively well the soft band of the spectrum ($\sim 0.1$–0.6 keV). A flatter second power law with $\Gamma_1 \sim 1$ is responsible for describing the hard band ($\sim 0.7$–10 keV). Extra absorption, above the Galactic value, arises naturally from the fit (with the same number of parameters as the pl+bb model). Material with a column density $N_{\text{H}} \approx 1.2 \times 10^{20}$ cm$^{-2}$ accounts for this extra absorption (see the best-fit column density in Table 2, row 6). We adjusted this model to have excess absorption of this best-fit column density plus $\Delta N_{\text{H}}$ and $2\Delta N_{\text{H}}$, and refit, obtaining worse fits (see rows 7 and 8 in Table 2). We conclude that there is little evidence for cold excess absorption with a column density of $N_{\text{H}} \sim 10^{21}$ cm$^{-2}$. The maximum amount of cold absorption we can hide in the X-ray spectrum of MR 2251–178, based on the model fit involving two power laws, is $N_{\text{H}} \approx 1.2 \times 10^{20}$ cm$^{-2}$, and we consider this to be a safe upper limit on the excess absorption along the line of sight at the epoch of observation.

From here on all the models considered in this study are multiplied by an absorption column of gas (phabs model in XSPEC) with $N_{\text{H}} = 2.77 \times 10^{20}$ cm$^{-2}$ to describe the Galactic absorption.

10 Power law plus blackbody modified by a column of gas in the AGN frame. The model is corrected for Galactic absorption.

11 See http://heasarc.nasa.gov/docs/xanadu/xspec/manual. The abundances are solar, from Anders & Grevesse (1989).
### TABLE 2
COLD ABSORPTION FIT RESULTS

| \(N_H^a\) | \(\Gamma_x\) | Normb | \(\Gamma_x(2)\) | Norm(2)b | kTc | Normd | \(\chi^2/dof\) |
|-----------|-------------|-------|-----------------|-----------|-----|-------|-------------|
| 1.68 \(\pm\) 0.07\(^a\) | 1.79 \(\pm\) 0.02 | 5.34 \(\pm\) 0.06 | ... | ... | ... | ... | 2.55/306 |
| 2.77\(^f\) | 1.94 \(\pm\) 0.02 | 5.65 \(\pm\) 0.06 | ... | ... | ... | ... | 3.00/307 |
| 3.27\(^g\) | 2.00 \(\pm\) 0.02 | 5.78 \(\pm\) 0.06 | ... | ... | ... | ... | 3.40/307 |
| 3.77\(^h\) | 2.05 \(\pm\) 0.02 | 5.91 \(\pm\) 0.06 | ... | ... | ... | ... | 3.85/307 |
| \(\leq 10^{-6}\) | 1.52 \(\pm\) 0.02 | 4.70 \(\pm\) 0.07 | ... | ... | 80.3 \(\pm\) 1.3 | 1.04 \(\pm\) 0.05 | 1.64/304 |
| 1.24 \(\pm\) 0.09 | 3.47 \(\pm\) 0.03 | 1.20 \(\pm\) 0.03 | 1.41 \(\pm\) 0.03 | 3.97 \(\pm\) 0.06 | ... | ... | 1.81/304 |
| 1.74\(^i\) | 3.70 \(\pm\) 0.03 | 1.04 \(\pm\) 0.03 | 1.44 \(\pm\) 0.02 | 4.16 \(\pm\) 0.06 | ... | ... | 1.81/305 |
| 2.24\(^j\) | 3.94 \(\pm\) 0.03 | 0.91 \(\pm\) 0.02 | 1.47 \(\pm\) 0.02 | 4.34 \(\pm\) 0.06 | ... | ... | 1.84/305 |

**Note.**—The error parameters are 90% confidence limits.

\(N_H^a\) Absorber column density in units of \(10^{20}\) cm\(^{-2}\).

b Power-law normalization, \(\times 10^{-5}\) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV.

c Temperature of the blackbody in eV.

d Value \(\times 10^{-6}\) in units of \(L_{39}/D_{10}^2\), where \(L_{39}\) is the luminosity of the source in units of \(10^{39}\) ergs s\(^{-1}\), and \(D_{10}\) the distance to the source in units of 10 kpc.

e Free parameter.

f Fixed to Galactic value.

g Fixed to Galactic value plus \(\Delta N_H\), where \(\Delta N_H = 5 \times 10^{19}\) cm\(^{-2}\).

h Fixed to Galactic value plus 2 \(\times\) \(\Delta N_H\).

i Extra absorber column density (shifted by \(z = 0.06398\), model zphabs in XSPEC), fixed to the best value plus \(\Delta N_H\). The fit is corrected by the Galactic absorption.

j Extra absorber column density (shifted by \(z = 0.06398\), model zphabs in XSPEC), fixed to the best value plus 2 \(\times\) \(\Delta N_H\). The fit is corrected by the Galactic absorption.

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**Fig. 4.**—LETGS spectrum of MR 2251–178 in the observed frame (positive and negative orders added). It is binned to have at least 100 counts from the source per bin. All the models include the Galactic absorption toward MR 2251–178 (see text). In the top panel the lines are as follows. Red: pl; green: pl+2edge; dark blue: pl+bb; light blue: (pl+bb) \(\times\) 2edge. The rest of the panels are the ratios of each composite model to the data, represented by their corresponding colors (pl=power law; bb=blackbody).

[See the electronic edition of the Journal for a color version of this figure.]
TABLE 3
RESULTS FROM SIMPLE MODEL FITS

| Model | $\Gamma_0$ | Norm | $\tau_{O\,\text{vi}}$ | $\tau_{O\,\text{vi}}$ | $kT$ | Norm | $\chi^2$/dof |
|-------|------------|------|----------------------|----------------------|------|------|-------------|
| 1.…… | 1.94 ± 0.02 | 5.65 ± 0.06 | ... | ... | ... | ... | 3.00(307) |
| 2.…… | 1.53 ± 0.02 | 4.73 ± 0.06 | ... | ... | 81.5 ± 2.0 | 9.94 ± 0.38 | 1.63(305) |
| 3.…… | 1.92 ± 0.02 | 6.53 ± 0.07 | 0.56 ± 0.04 | 0.22 ± 0.05 | ... | 1.38(305) |
| 4.…… | 1.85 ± 0.02 | 6.35 ± 0.07 | 0.51 ± 0.04 | 0.21 ± 0.04 | 44.1 ± 3.0 | 5.57 ± 0.92 | 1.25(303) |

Note.—All the models include absorption fixed at the Galactic value of $N_H = 2.77 \times 10^{20}$ cm$^{-2}$. The error parameters are 90% confidence limits.

*a* Power-law normalization, in units of $10^{20}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.

*b* Temperature of the blackbody in eV.

*c* Value $\times 10^{-5}$ in units of $L_{39}/D_{10}$, where $L_{39}$ is the luminosity of the source in units of $10^{39}$ ergs s$^{-1}$, and $D_{10}$ the distance to the source in units of 10 kpc.

toward MR 2251–178 (Lockman & Savage 1995). First, we focus our attention on the fit of a power law to describe the 1.24–124 Å band of the spectrum. A single power law gives $\Gamma_0 = 1.94 ± 0.02$, with large residuals (i.e., 15%–40%) at $\sim 1.2$–7 Å and close to 18 Å (see Fig. 4), and a poor statistical fit quality of $\chi^2_{\nu} = 3.00$. We included a thermal component to account for any soft X-ray excess. A blackbody with a temperature of $kT = 81.5 \pm 2.0$ eV significantly improved the fit with $\chi^2_{\nu} = 1.63$ (for $\text{dof} = 305$). With this addition, the slope of the power law changes to a flatter value of $\Gamma_0 = 1.53 ± 0.02$, and the model agrees with the data within 30% almost from $\sim 1.2$ to 40 Å, except for the residual around 18 Å.

Now let us consider the absorption features at $\sim 18$ and $\sim 15$ Å in turn. Komossa (2001) fitted a power law with two edges at the theoretical positions of O vii and O viii, 739 and 871 eV, respectively, representing the warm absorber, and obtained $\tau_{O\,\text{vi}} = 0.22 ± 0.11$ and $\tau_{O\,\text{viii}} = 0.24 ± 0.12$. The high sensitivity and resolution of the Chandra LETG spectrometer coupled with the good quality of the observation of MR 2251–178 allow us to fit these features with a high precision. Our pl2edges ($\sim 18$ and $\sim 15$ Å in the observed frame) model gives us a significant improvement ($\chi^2_{\nu} = 1.38$ for 305 dof) over the fit of the power law alone ($\chi^2_{\nu} = 3.00$ for 307 dof) and the power law plus the blackbody component as well ($\chi^2_{\nu} = 1.63$ for 305 dof). This model is in agreement with the data $\approx 15\%$ (data/model $\approx 1.00 ± 0.15$; Fig. 4) over almost the entire spectrum, except for the wavelength range 1.2–6 Å (and possibly at wavelengths $\geq 60$ Å, but see the large errors). The continuum optical depths are $\tau_{O\,\text{vii}} = 0.56 ± 0.05$ and $\tau_{O\,\text{viii}} = 0.22 ± 0.05$. We compare these values with those obtained from ROSAT. In the case of O viii they appear to agree within the error bars. However, in the case of O vii the optical depth is approximately a factor of 2.5 higher. In this direct comparison model to model, the Chandra data suggests that the contribution of this feature has changed over the years ($\sim 15$).

Finally, we can build a model combining all the ingredients mentioned above, leading us to a global view of the spectrum: a power law plus a soft thermal component modified by two warm absorber edges. This model is shown in Figure 4, and the maximum deviation of the ratio data/model is $\pm 15\%$ over almost the entire spectrum, with $\chi^2_{\nu} = 1.25$ (for 303 dof). The F-test identifies this improvement (the inclusion of the blackbody emission) as significant (at $\approx 99\%$ significance level) over the pl2edges model. The blackbody has a temperature of $kT \sim 50$ eV, with the slope of the power law in agreement with other models of this study ($\sim 1.7–2$) and with slopes reported by previous missions (i.e., ROSAT), but not with the flatter slope of $\sim 1.4$ reported recently by Gibson et al. (2005) in the HETGS observation of the same object. We can see that the inclusion of the strong O vii feature displaces the temperature of the blackbody from $kT = \sim 80$ to $50$ eV with respect to the pl2bb without edges. The reduced temperature of the bb helps to improve the fit in the range $\sim 20$–60 Å, giving an improvement of $\Delta \chi^2 \approx 110$. The model parameters are quoted in Table 3. The four models are plotted in Figure 4 on the background-subtracted count-rate spectrum of MR 2251–178 in the wavelength space (rebinned to have at least 100 counts from the source per bin).

3.3. A Dusty Warm Absorber

Dusty warm absorbers have been found to imprint their hallmark on the X-ray spectra of several AGNs (e.g., Komossa & Fink 1997; Komossa & Bade 1998; Lee et al. 2001). We investigate the possibility of the presence of a dusty warm absorber by looking at the position of two important edges that are predicted to be strong and noticeable in the X-ray band: the neutral carbon edge at 291 eV (from the graphite species) and the O i edge at 538 eV (from silicates). Figure 5 shows the position of these two edges (the edges corresponding to the H- and He-like oxygen features are included in the model, but they lie off the figure axis), in the observer’s frame (also labelled is the Galactic neutral oxygen, as O i$_{\text{gal}}$). These edges are not clearly seen in the spectrum, but this does not preclude their potential addition and improvement to the model in the fitting. In Table 4 we present the result of fitting the spectrum of MR 2251–178 with a model that is composed of a Galactic absorbed power law modified by four edges, the K edges of C i, O i, O vii, and O viii. In order to search for fine features, we used a larger number of bins in the fit, with 50 counts from the source per bin. In terms of the goodness of fit, this is equal to the pl2edges model, with $\chi^2_{\nu} = 1.22$ (for 587 dof). However, letting the four edges vary freely, the C i optical depths has no lower limits. An upper limit can be set on the dusty material if it exists. We held $\tau_{C\,\text{i}}$ equal to 0.08 (the upper limit of this measurements), leaving all the other optical depths free to vary, and refit. We set this as an upper limit on the $\tau_{C\,\text{i}}$ parameter, since the fit does not get worse with respect to the previous one (see row 2 in Table 4). This translates to a C i column density $N_{C\,\text{i}} \approx 2 \times 10^{19}$ cm$^{-2}$. Doing the same with the $\tau_{O\,\text{i}}$ (taking the upper limit of the best fit), we obtain no significant change with respect to the best-fit $\chi^2$ (see row 3), and we consider $\tau_{O\,\text{i}} = 0.09$ to be the upper limit on $\tau_{O\,\text{i}}$, which translates to $N_{O\,\text{i}} \approx 9 \times 10^{19}$ cm$^{-2}$ (we used the photoionization cross sections from Morrison & McCammon [1983] at their respective energies). For typical Galactic gas/dust ratios, our observed upper limit is not sensitive enough to provide significant constraints on the dust in MR 2251–178.

3.4. Mean Warm Absorber

In this section we discuss the global view of the spectrum of MR 2251–178 in terms of a more physical model. Visually, the
The strongest spectral feature is the broad absorption structure around 17 Å (see Fig. 6), which is recognized as the hallmark of a warm absorber (e.g., George et al. 1998). Detailed calculations have demonstrated that this structure is made (mainly) by the O vii K edge and by the Fe M shell 2p→3d unresolved transition array (UTA) between 16 and 17 Å (Behar et al. 2001). The ionization condition under this structure is strong enough to dominate the emergent spectrum, and has been the subject of several theoretical and observational works (e.g., Krongold et al. 2003; Gu et al. 2006), due to in part to the particular sensitivity of this feature to the ionization state of the gas responsible for the absorption.

To describe the state of the gas, we build a grid of photoionization models, assuming ionization and thermal equilibrium. Under conditions of ionization equilibrium, the state of the gas...
depends mostly (apart from \(n_H\), abundances, and column density) on the shape of the ionizing spectrum and the ionization parameter \(\xi\), which we define as in Tarter et al. (1969): 

\[
\xi = \frac{4\pi F_{\text{ion}}}{n_H},
\]

where \(F_{\text{ion}}\) is the total ionizing flux \([F_{\text{ion}} = L_{\text{ion}}/(4\pi^2)]\); see below for definition of \(L_{\text{ion}}\), and \(n_H\) is the gas density. We have carried out all the photoionization calculations using the XSTAR\textsuperscript{12} code with the atomic data of Bautista & Kallman (2001). The code includes all the relevant atomic processes (including inner shell processes) and computes the emissivities and optical depths of the most prominent X-ray and UV lines identified in AGN spectra. Our models are based on spherical shells illuminated by a pointlike X-ray continuum source. The input parameters are the source spectrum, the gas composition, the gas density \(n_H\), the column density, and the ionization parameter. The source spectrum is described by the spectral luminosity \(L_\lambda = L_{\text{ion}} f_\lambda\), where \(L_{\text{ion}}\) is the integrated luminosity from 1 to 1000 ryd, and \(f_\lambda^{1000\text{ryd}}\) and \(d\chi = 1.0\). The spectral function is taken to be the ionizing spectrum of Leighly (2004). The gas consists of the following elements: H, He, C, N, O, Ne, Mg, Si, S, Ar, Ca, and Fe. We use the abundances of Grevesse et al. (1996) in all our models (we use the term solar for these abundances). We adopt a turbulent velocity of 100 km s\(^{-1}\) and a gas density \(n_H = 10^8\) cm\(^{-3}\).

3.4.1. Global Absorption

We have fit the X-ray spectrum of MR 2251–178 with our XSTAR-based photoionization models. First of all, we find that independent of column density, a relatively low ionization parameter is needed; otherwise, the spectrum in the Fe UTA band is

![Fig. 6.—The 10–40 Å spectrum of MR 2251–178 and XSTAR photoionization models of different ionization parameters. We use \(N_H = 4 \times 10^{21}\) cm\(^{-2}\) for illustrative purposes. Top: High-ionization state, \(\log(\xi) = 1.5\) and 2 (black and red lines, respectively). Bottom: Lower ionization state, \(\log(\xi) = 0.5\), 0.7, and 0.9 (black, red, and blue lines, respectively). It can be observed that at higher \(\log(\xi)\), the produced absorption feature is at bluer wavelengths. [See the electronic edition of the Journal for a color version of this figure.]](image-url)
not well reproduced. We demonstrate this point in Figure 6. It shows the resulting absorption spectrum for several ionization states. For illustrative purposes, here we fix $N_{\text{H}} = 4 \times 10^{21}$ cm$^{-2}$.

In the top panel we can see the spectrum resulting at the high-ionization parameter, log($\xi$) = 1.5 and 2. The bottom panel shows the spectrum at lower ionization states, with log($\xi$) = 0.5, 0.7, and 0.9, in black, red, and dark blue, respectively. From this we can rule out high-ionization states alone as describing this band because these models always give large residuals in the UTA band (see below).

Nevertheless, for our best-fit, single-component photoionization model (pl x XSTARMODEL; Fig. 7), we obtain the following parameters: a column density of $N_{\text{H}} = 4.77^{+0.31}_{-0.29} \times 10^{21}$ cm$^{-2}$, an ionization parameter log ($\xi$) = 1.83 $\pm$ 0.06, and a photon index $\Gamma_x = 1.96 \pm 0.02$. While the fit well describes the long-wavelength part of the absorption feature (with respect to the centroid around $\sim$ 17.4 Å), there exists a large residual in the shorter wavelength range ($\geq$50%), resulting in a fit with $\chi^2_\nu = 1.54$ (for 587 dof). Motivated by the good result of including a thermal component to describe any soft excess, and also by the fact that the X-ray spectrum of this object has been fitted before including a thermal component (for example in Gibson et al. 2005), we include in our model a blackbody, characterized by its temperature $kT$ [i.e., (pl+bb) x XSTARMODEL = X_2]. The inclusion of the blackbody improved the fit, which gives $\chi^2_\nu = 1.27$ (and dof = 585). But we went further and considered the possibility that the absorbing gas in MR 2251-178 is flowing outward from the center of the system with velocities $v_\parallel$ -200 km s$^{-1}$. For that purpose we shift the modeled spectrum (the absorber) by a grid of velocities, keeping fixed the outflow velocity and leaving the other parameters of interest free to vary. For X_1 we found that it favors an outflow velocity $\approx$200 km s$^{-1}$. In the case of X_2, the model points to an outflow velocity $\approx$1200 km s$^{-1}$. After finding statistically motivated outflow velocities for our models, we were able to thaw them and find the best-fit outflow velocity.

The XSTARMODEL plus the blackbody (X_4) gives a $\chi^2_\nu = 1.22$ (with dof = 584) and the following best-fit parameters: $N_{\text{H}} = 2.25^{+0.28}_{-0.25} \times 10^{21}$ cm$^{-2}$, log ($\xi$) = 0.63 $\pm$ 0.06, $kT = 89.5 \pm 2.5$ eV.

---

13 Although Kaspi et al. [2004] reported using a multicomponent model to represent the spectrum of MR 2251-178, we were not able to find a significant improvement on the fit over the one-absorber component.
and \( v_{\text{out}} = -1100 \pm 60 \) km s\(^{-1}\). An inspection of Figure 7 reveals a good agreement between the data and the model, and the removal of the residual around \(\lambda \approx 17 \) Å (see the ratio data/model).\(^{14}\) Table 5 summarizes the parameter values of the model with and without the thermal component, at rest (i.e., 0 km s\(^{-1}\)) and with the best-fit outflow velocity. We present in Figures 8 and 9 a high-resolution (bin size 25 mÅ) version of our best-photoionization model plotted over the spectrum of MR 2251–178 (in the most interesting range to search for spectral lines, \(\sim 1–40 \) Å). Here we fix the velocity outflow to the best-fit value found above (i.e., \( v_{\text{out}} = 1100 \) km s\(^{-1}\)) and leave the other parameters free to vary (i.e., \( x_1 = 1.66 \pm 0.02 \), \( N_H = 1.82 \pm 0.03 \times 10^{21} \) cm\(^{-2}\), \( \log (\xi) = 0.57 \pm 0.09 \), and \( kT = 95.2 \pm 1.3 \) eV). We use our best-fit featureless continuum (but including bound-free transitions) as the underlying continuum.

\(^{14}\) In order to see if a multicomponent warm absorber system is supported by the data we repeat the above procedure adding a second warm absorber system to the models, without (\(X_5\)) and with the blackbody (\(X_6\)). In general the data do not well constrain the parameters of the second component. And in any case, no significant improvement is seen by adding a second component to our model (i.e., \( \chi^2 \approx 707 \), \( \Delta \chi^2 \approx 6 \) better than \(X_4\)), and we do not discuss this model further.

**TABLE 5**

**FIT RESULTS FOR PHOTONIZATION MODELS**

| Parameter | \(X_1\) | \(X_2\) | \(X_3\) | \(X_4\) |
|-----------|---------|---------|---------|---------|
| \(\Gamma\) | 1.96 ± 0.02 | 1.66 ± 0.02 | 1.97 ± 0.02 | 1.66 ± 0.02 |
| Norm\(^a\) | 6.84 ± 0.07 | 5.42 ± 0.07 | 6.82 ± 0.07 | 5.38 ± 0.07 |
| \(kT\) (eV) | \ldots | 89.9 \pm 2.5 | \ldots | 89.5 ± 2.5 |
| Norm\(_{bb}\) | \ldots | 10.21 ± 0.42 | \ldots | 10.29 \pm 0.44 |
| \(N_H\) | 4.77 \pm 0.31 | 2.44 \pm 0.31 | 4.28 \pm 0.29 | 2.28 \pm 0.28 |
| \(\log (\xi)\) | 1.83 ± 0.06 | 0.64 \pm 0.06 | 1.72 ± 0.07 | 0.63 ± 0.06 |
| \(v_{\text{out}}\) | 0 | 0 | 340 \pm 120 | 1100 \pm 210 |
| \(\chi^2/\text{dof}\) | 1.54(587) | 1.27(585) | 1.52(586) | 1.22(584) |

\(^{a}\)Power-law normalization, in units of \(10^{-3}\) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV.

\(^b\)Value \(\times 10^{-5}\) in units of \(L_39/D_10\), where \(L_39\) is the luminosity of the source in units of \(10^{39}\) ergs s\(^{-1}\), and \(D_10\) the distance to the source in units of 10 kpc.

\(^c\)Column density of the ionized material in units of \(10^{21}\) cm\(^{-2}\).

\(^d\)Outflow velocity of the ionized gas in units of km s\(^{-1}\). Models \(X_1–X_4\) are described in the text (see \(\S\) 3.4.1).

**Fig. 8.—** Comparison of the 1–22 Å spectrum of MR 2251–178 with our best-fit XSTAR photoionization model, which is presented in high resolution (bin size 25 mÅ). The physical model is shifted by \(-1100\) km s\(^{-1}\). The predicted lines of Ne, Fe, and O are labelled at the top of the spectrum. [See the electronic edition of the Journal for a color version of this figure.]
for the search for possible spectral lines (also plotted in Fig. 8), as discussed in the next section.

3.4.2. Absorption Lines

There are several coincidences between the theoretical prediction about where a line is located and deviations of the data from the fit continuum (the XSTAR featureless global continuum described above). In order to look for narrow absorption features (in a systematic way) in the spectrum, we use a finer binned spectrum (bin size 25 mÅ). We use the following detection criteria:

1. The counts present in the data must deviate from the fit continuum by at least 1σ. As the underlying continuum, we use the best-fit global featureless continuum described above. We use a global continuum fit because in that way we are less sensitive to local noise in the spectrum.15

2. The FWHM (within errors) of the line should not be significantly smaller than the instrumental FWHM at the corresponding wavelength.

Not as a criterion, but as an extra piece of statistical evidence for the presence of lines, we use the maximum likelihood ratio (MLR) test to compare the continuum model with the continuum+line model and compute the line significance (see Table 6, col. [4]). \( P(\geq T) \) is the probability that one would select

\[
\chi^2 \text{ (reduction fits)} = \frac{\chi^2 \text{ (observed counts minus model counts)}}{N - p}
\]

\( \chi^2 \) is the goodness of fit for the observed counts minus the model counts, where \( N \) is the number of data points and \( p \) is the number of free parameters.

26.34 ± 0.01 .................................. 160 ± 100 242 7.38 × 10^{-3}
30.09 ± 0.02 .................................. 190 ± 100 212 1.13 × 10^{-3}
30.32 ± 0.03 .................................. 280 ± 100 210 7.06 × 10^{-4}
35.83 ± 0.03 .................................. 220 ± 100 178 1.17 × 10^{-2}

\( \text{Notes.} \) — Error parameters are 90% confidence limits. The final significance is less than the one shown in col. (4), since the number of trials is not considered. The MLR test is described in § 3.4.2.

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15 As a test of the robustness of our results, we have also determined the continuum locally around the line. The continuum was fit locally (±0.5 Å) as a power law. We find that all four key line candidates are still present when a local continuum is used. To give an example: the equivalent width of the \( K\alpha \) line of N vi (see Table 7) changes from \( 55^{+06}_{-05} \) to \( \approx 70 \) mÅ, when using a local continuum. The measurements of the other three lines are unaffected by the local continuum fit.
the more complex model (continuum+line) when in fact the null hypothesis is correct (continuum alone). We set a lower threshold of $P(\geq T) < 0.01$ (not accounting for number of trials). In fact, the four features that passed criteria 1 and 2 also had $P(\geq T)$ below this threshold (see Band et al. 1997 for a justification for using the MLR test).

A list of candidate absorption lines is given in Table 6. We measure the center (col. [1]), and the width (in terms of $\sigma$, in km s$^{-1}$; col. [2]) of each spectral structure using the best-fit continuum described above.

Figure 10 shows different portions of the spectrum containing absorption lines. Among these lines, we only report measurements from four lines (Table 7), located in a region where the calibration of the LETGS is reliable and its sensitivity is high enough to report 90% confidence limits on their errors. Deviations, but with an FWHM too low to be reported as individual lines, are still marked in the figure (panel), but are not discussed here any further.

The measurements of the line parameters along with their identification are given in Table 7. In the first column we have the center of the line, and in the second column the equivalent width (EW) of the line in milliangstroms, computed with

$$\text{EW} = \int \left[ 1 - \frac{F_c(\lambda)}{F_c(\lambda)} \right] d\lambda,$$

where $F_c(\lambda) = F_c(\lambda)(1 - \tau_0 \exp[-(\lambda - \lambda_0)^2/(2\sigma^2)])$. $F_c(\lambda)$ is the continuum at the wavelength $\lambda$, $\tau_0$ is the depth at the center of the line, $\sigma$ is the measured width in angstroms, and $\lambda_0$ is the wavelength of the line in Å (at the core). The EW uncertainties are computed using the lower and upper limits of $\tau_0$ and $\sigma$ (i.e, $\text{EW}_{\min} = \text{EW}[\tau_{\min}, \sigma_{\min}]$ and $\text{EW}_{\max} = \text{EW}[\tau_{\max}, \sigma_{\max}]$).

In the fourth column we give the blueshift of the line (in km s$^{-1}$). All these are resonance lines, product of electric dipole transitions with the form 1$s$–np for C and 1$s$–1$snp$ for N ions.

We discuss the issue of line identification in two steps: (1) As a first (simplifying) step we assume that the spectrum is dominated by only one main warm absorber and that the column density and ionization parameter from the global fit to the X-ray spectrum characterize this main warm absorber reasonably well. Then this
best-fit global warm absorber model guides us in identifying the absorption lines seen in the spectrum. In this first step, we only consider line identification with transitions, which are actually being predicted to be strong (i.e., detectable) by this photoionization model. If no line feature at zero velocity was predicted by the model, we allowed for a range of velocities (up to a few thousand km s\(^{-1}\))—a range of outflow velocities commonly observed in known warm absorbers. That procedure resulted in the line identification reported in Table 7. To give an example of a possible alternative identification, we compare the strength of the line N\(^{\text{vi}}\) at 24.9 Å (1–2p; the one identified in Table 7) with a potential alternative identification, the N\(^{\text{vii}}\) at 24.8 Å. The former line is much stronger than the latter: the ratio of optical depth at the core is \(\tau(\text{N}\text{vi})/\tau(\text{N}\text{vii}) \approx 8\), for our best-fit global ionization parameter of \(\log(\xi) = 0.6\). At this \(\log(\xi)\), there is almost 3.5 times more N\(^{\text{vi}}\) than N\(^{\text{vii}}\).

Assuming that the one-absorber model is correct, the predicted strongest lines are the four-line candidates presented in Table 7. However, we find that lines coming from the same ion are at different outflow velocity. This is a problem at the moment, and it opens up a second possibility, which we examined in a second step: (2) the possibility that we see several different warm absorber components, each with a different outflow velocity and each characterized by a potentially different column density and ionization parameter. The data quality, a single grating exposure of only 80 ks, does not allow to fit such a four-component absorber with so many free parameters. Therefore, in step 2 we made the (simplifying) assumption that the four identified lines are all at the same velocity. We therefore assumed that all four lines are at zero velocity or at velocities up to \(\pm 500\) km s\(^{-1}\), in particular. Independent of any warm absorber model (i.e., any specific \(\xi\) and \(N_\text{H}\)), we searched line lists to find any consistent line identifications for the four lines, fixing their wavelengths to the quasar rest-frame (i.e., assuming zero velocity), or allowing velocities up to \(\pm 500\) km s\(^{-1}\). In that case, no line counterparts can be identified.

We therefore continue with solution 1, and discuss some implications of this solution. Since most warm absorbers are not at rest, in order to identify lines we allowed for a range of outflow velocities, from 0 to 5000 km s\(^{-1}\). We find that not all of the absorption-line candidates are at the same outflow velocity, but we make preliminary identifications of three velocity systems at \(\sim 600\), \(\sim 2000\), and \(\sim 3000\) km s\(^{-1}\). Further discussion of these three components and a comparison with UV observations are provided in § 5.

4. VARIABILITY IN THE 0.6–1 keV BAND

The region \((0.6–1)\) keV in the spectrum of MR 2251–178 is complex, due to the presence and blending of three features: the Fe UTA, and the K edges of oxygen O\(^{\text{vii}}\) and O\(^{\text{viii}}\). As a first step, we investigate temporal changes assuming the spectrum is actually dominated by the O\(^{\text{vii}}\) and O\(^{\text{viii}}\) edges. Later, in § 5.2, we carefully discuss the variability of the spectrum based on this photoionization model, which includes a proper treatment of these features, including the UTA self-consistently. First, we split the observation into four (1–4) Good Time Intervals (GTIs; equally distributed, \(\sim 11\) ks) and applied a \(\pm 2\) edges model to each set of data. By fitting this model (with the edges’ energy fixed at the values of the O\(^{\text{vii}}\) and O\(^{\text{viii}}\) K edges, 739 and 871 eV, respectively), we are able to notice changes (in time) around the bound-free features, at \(\sim 0.69\) keV for O\(^{\text{vii}}\) and 0.81 keV for O\(^{\text{viii}}\) in the observed frame, which in turn modify the parameter values of the model (see Table 8). To quantify these changes we looked at the parameters of the model at each time interval. Due to the low S/N of the data, these measurements have large errors. Nevertheless, one real inconsistency is seen in the depth of the O\(^{\text{vii}}\) edge (\(\tau_{\text{O vii}}\)) from time interval 1 to 3: approximately a factor of 3.4 in \(\tau_{\text{O vii}}\) leads to a change in the count rate level of \(\sim 20\%\), in the vicinity of the edge. Almost no change is seen in \(\tau_{\text{O viii}}\), being consistently close to the mean best-fit value found before, \(\tau_{\text{O viii}} \approx 0.6\).

We caution that the edge model is an overly simple representation of the spectrum in the 0.6–1 keV range, where the UTAs are also located. Therefore, we do not draw any physical implications from it. We discuss a more physical photoionization model in § 5.2.

5. DISCUSSION

In this section we discuss the physical implications of our measurements, which allow us to draw conclusions about the kinematics of the outflowing gas, ionization state of the warm absorber, and variability of the absorption structure around the oxygen edges seen in the spectrum of MR 2251–178.

5.1. Identification of Absorption Lines

The identification of absorption lines in the X-ray spectra of AGNs is important because these lines carry a wealth of information on the physical conditions in the ionized gas and its link to other components of the active nucleus.

### Table 7

| \(\lambda_{\text{obs}}\) (Å) | EW (mÅ) | Ion and Atomic Transition | \(\lambda_{\text{lab}}\) (Å) | \(v_{\text{lab}}\) (km s\(^{-1}\)) |
|--------------------------|--------|---------------------------|--------------------------|------------------|
| 26.34 \(\pm 0.03\)      | 55 \(\pm 30\) | N\(^{\text{vi}}\) 1s\(^{2}\)3s\(^{2}\)1p\(^{3}\)P\(^{0}\) | 24.914 | \(-2030 \(\pm 260\)\) |
| 30.09 \(\pm 0.02\)      | 63 \(\pm 24\) | C\(^{\text{iv}}\) 1s\(^{2}\)2p\(^{3}\)P\(^{0}\) | 28.466 | \(-2080 \pm 210\) |
| 32.82 \(\pm 0.02\)      | 70 \(\pm 20\) | N\(^{\text{vi}}\) 1s\(^{2}\)3s\(^{2}\)1p\(^{3}\)P\(^{0}\) | 28.787 | \(-3220 \(\pm 210\)\) |
| 35.83 \(\pm 0.03\)      | 86 \(\pm 16\) | C\(^{\text{ix}}\) 1s\(^{2}\)2s\(^{2}\)2p\(^{3}\)P\(^{0}\) | 33.736 | \(-580 \pm 270\) |

Note.—Errors are 90% confidence limits.

### Table 8

| Period | \(t_{\text{out}} \times 10^{18}\) (s) | \(t_{\text{end}} \times 10^{8}\) (s) | Total Counts \((\times 10^{8})\) | \(\Gamma_{k}\) | Norm\(a\) | \(\tau_{\text{O vii}}\) | \(\tau_{\text{O viii}}\) | \(\chi_{p}^{2}/\text{dof}\) |
|--------|------------------|------------------|-----------------------------|--------|--------|----------------|----------------|----------------|
| 1.      | 1.570487477      | 1.570653992      | 1.8298                      | 1.90 \(\pm 0.04\) | 6.11 \(\pm 0.13\) | 0.57 \(\pm 0.09\) | 0.09 \(\pm 0.08\) | 1.19/161       |
| 2.      | 1.570653993      | 1.570819941      | 1.6404                      | 1.89 \(\pm 0.04\) | 6.58 \(\pm 0.14\) | 0.67 \(\pm 0.10\) | 0.25 \(\pm 0.10\) | 1.01/145       |
| 3.      | 1.570879942      | 1.570982180      | 1.7391                      | 1.91 \(\pm 0.04\) | 6.62 \(\pm 0.14\) | 0.46 \(\pm 0.09\) | 0.31 \(\pm 0.09\) | 1.32/159       |
| 4.      | 1.570992818      | 1.571276092      | 1.5842                      | 1.96 \(\pm 0.04\) | 6.61 \(\pm 0.15\) | 0.57 \(\pm 0.09\) | 0.22 \(\pm 0.10\) | 1.39/144       |

Note.—The model includes Galactic absorption of \(N_{\text{H}} = 2.77 \times 10^{20}\) cm\(^{-2}\). The error parameters are 90% confidence limits computed with the spectrum adaptively binned to have at least 50 counts from the source per bin.

\(a\) In the detector (original) time. These intervals exclude data from the “bad time intervals” (§ 2.1).

\(b\) Power-law normalization, in units of \(10^{-9}\) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV.
We have systematically searched for absorption- and emission-line features in the X-ray spectrum of MR 2251–178 and have identified four absorption-line candidates corresponding to transitions in the ions C vi and N vi. These lines, if real, would imply a rather complex velocity field of the absorber, with lines from the same ion indicating different outflow velocities. Of particular concern is the lack of corresponding absorption from the element oxygen. In cases of solar abundances of the ionization lines, observed with the STIS (2004) report some oxygen absorption features at 16–22 Å in the RGS spectrum of MR 2251–178 (their Table 3), albeit with low significance.

| Ion  | \( M^d \) (Monier et al. 2001) | \( M^d \) (Monier et al. 2001) | \( \frac{1}{2} M^e v^2 \) (ergs s\(^{-1} \)) | \( M^d \) (Monier et al. 2001) | \( \frac{1}{2} M^e v^2 \) (ergs s\(^{-1} \)) |
|------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C iv | 0.9             | ...             | ...             | ...             | ...             |
| Fe xxvi | ... | 220 \( f_{\text{cov}} \) | 1.1 \( \times 10^{46} f_{\text{cov}} \) | ... | ... |
| Fe xvii | ... | 8900 \( f_{\text{cov}} \) | 7.9 \( \times 10^{47} f_{\text{cov}} \) | ... | ... |
| S xiv | ... | 1700 \( f_{\text{cov}} \) | 1.6 \( \times 10^{47} f_{\text{cov}} \) | ... | ... |
| N vi | ... | ... | 0.18 \( f_{\text{cov}} \) | 6.7 \( \times 10^{46} f_{\text{cov}} \) | ... |
| C vi | ... | ... | 0.32 \( f_{\text{cov}} \) | 4.0 \( \times 10^{46} f_{\text{cov}} \) | ... |

\( f_{\text{cov}} \) present work.

\( f_{\text{cov}} \) best-fit outflow velocity found in § 3.4 of 1100 km s\(^{-1} \).

Using the velocities shown by the lines in Table 7 (and \( N_H = 10^{21.35} \) cm\(^{-2} \), of \( \approx 2000 \) and 3000 km s\(^{-1} \) for the N and C lines, respectively.

Monier et al. (2001) using the Ly\( \alpha \), N v \( \lambda 1240 \), and C iv \( \lambda 1549 \) lines in the UV band (with the HST Faint Object Spectrograph observation of MR 2251–178).

To compute the mass-outflow rate, we assume that the outflow material in MR 2251–178 forms a spherical shell (\( n \propto r^2 \)) expanding at velocity \( v \). Using the approximation \( N \approx nr \), we can write

\[
\dot{M}_{\text{out}} = 4\pi \mu_H N r v f_{\text{cov}},
\]

or

\[
\dot{M}_{\text{out}} \approx 0.048 N_{21} r_{18} \left( \frac{v}{1000 \text{ km s}^{-1}} \right) f_{\text{cov}} M_2 \text{ yr}^{-1},
\]

where \( \mu_H \) is the mean mass per H atom (equal to \( m_p/0.7 \)), \( N_{21} \) is the column density of the material in units of \( 10^{21} \) cm\(^{-2} \), \( r_{18} \) is the distance of the gas in units of \( 10^{18} \) cm, and \( f_{\text{cov}} \) is the covering factor (\( \Omega/4\pi \)). Using our best-fit \( N_{21} \approx 10^{21.35} \) and an outflow velocity \( v = 1100 \) km s\(^{-1} \) at a distance of \( 1.5 \times 10^{18} \) cm (distance chosen for illustrative purposes), we have a mass-loss rate \( \dot{M}_{\text{out}} \approx 0.18 f_{\text{cov}} M_2 \text{ yr}^{-1} \).

In Table 9 we quote our estimate of the mass-loss rate of the LETG X-ray warm absorber system compared with previous values. To compute the mass-loss rate, Gibson et al. (2005) used a high-velocity outflow \( v \approx 13,000 \) km s\(^{-1} \), concluding that \( \dot{M}_{\text{out}} \) could significantly exceed the accretion rate \( (\sim 0.2 M_2 \text{ yr}^{-1} \) by \( \sim 1–2 \) orders of magnitude, even taking the Fe xxvi line (see Table 7 of that paper). On the other hand, Monier et al. (2001), using an outflow velocity of \( 300 \) km s\(^{-1} \), estimate a mass-loss rate of \( \sim 0.9 M_2 \text{ yr}^{-1} \) for a 10% covering factor, putting this value close to the accretion rate. Our computation of solar mass is more in agreement with the value found by these latter authors. The kinematic energy rate carried away by the flow spans \( (0.07–1) \times 10^{46} f_{\text{cov}} \) ergs s\(^{-1} \).

### 5.2. Absorption Variability during the Observation

Warm absorbers are known to vary on short and long time-scales. We find indications for variability during the LETG observation of MR 2251–178 in the wavelength range that includes the oxygen absorption edges and the Fe UTA features. Both the UTAs (e.g., Krongold et al. 2005) and/or the absorption edges could be variable. Mechanisms of variability include changes of the ionization state of the absorber to changes in the ionizing
continuum, changes of the internal structure of the absorber, and clouds crossing our line of sight.

In order to find clues to the variability mechanism, we have fit our most successful warm absorber photoionization model [model X4; i.e., (pl+bb)xstar, with $v_{\text{out}} = -1100$ km s$^{-1}$] separately to the four subsets of the total observation (Fig. 2). We have explored the effects of variable column density, ionization parameter, and intensity of the continuum (black body and power law) spectral components. The strongest effect is a change in column density of the ionizing material in epoch 3; formally requiring (at $k < 6/27$) a smaller column density in order to fit that epoch successfully (Fig. 11). In order to recheck whether the data do indicate variability between the different epochs, we have used the best-fit model of epoch 1 and compared it to the data of epoch 3. In the comparison, we have fixed all the parameters (of our model X4) to those derived for epoch 1, and then inspected the residuals during epoch 3. Clear deviations are seen (Fig. 12), demonstrating independently the presence of spectral changes throughout the observation.

Changes in the luminosity would affect the ionization state of the absorber, but the average count rate of MR2251–178 does not vary throughout the observation. Taken at face value, a true change in column density would require a change in density and/or thickness of the absorber, and we first briefly comment on this possibility.

Assuming the thickness of the absorber has not changed in such a short time, the density of the absorber would need to change by a factor of 3 to account for the change in $N_{\text{H}}$ between periods 1 and 3. However, changing the density of the whole extended gas (or a fraction of the gas by a large amount) is not easy on such a short timescale. Rearrangements of clouds crossing our line of sight would have to occur within $\gtrsim 10$ ks, which is very unlikely. Alternatively, we may see nonequilibrium ionization effects in the gas, in which the material responds with some time delay in a complicated way to previous variability in the ionizing continuum, which was not within our observation time window. Deeper observations with longer time bases are required to investigate these possibilities further.

6. CONCLUSIONS

The measured 0.1–2 keV flux $f_{0.1-2\text{keV}} = 2.58^{+0.04}_{-0.03} \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ implies that MR 2251–178 is in a relatively low state. The soft X-ray luminosity amounts to $L_{0.1-2\text{keV}} = 2.54 \times 10^{44}$ ergs s$^{-1}$.

We did not find any strong evidence for the presence of any extra cold material with a column density of $N_{\text{H}} \sim 10^{21}$ cm$^{-2}$.
toward MR 2251−178 (if part of this is located along our line of sight). Based on different spectral fits, we set the upper limit of this component to $N_{\text{cold}} \lesssim 1.2 \times 10^{20} \text{ cm}^{-2}$.

As for previous observations of MR 2251−178, a power law plus blackbody does not provide a successful fit to the X-ray spectrum. The addition of a warm absorber improves the fit significantly.

Based on XSTAR photoionization modeling, we find the observation to be consistent with ionized absorbing material in our line of sight, a column density $N_{\text{H}} \approx 2 \times 10^{21} \text{ cm}^{-2}$, and an ionization parameter of $\log \xi \approx 0.6$. The inclusion of an additional thermal component is important because otherwise: (1) the absorption structure around $18$ Å is not well reproduced; and (2) the ionization state of the gas would be higher, introducing a lot of problems in the identification of the atomic line transition. The temperature of the blackbody used to represent this thermal component is $kT \approx 90 \text{ eV}$.

We find four line candidates at moderate confidence level. If these lines are real, their presence would imply three components traveling at velocities $\sim 600$, $2000$, and $3000 \text{ km s}^{-1}$. We compute $M \sim 0.01−0.1 \, M_\odot \, \text{yr}^{-1}$ and a kinematic energy of $\sim 10^{42}$ ergs $\text{s}^{-1}$, using the C vi and N vi lines outflowing at velocities of $\sim 2000−3000 \text{ km s}^{-1}$.

Using $f_{\text{cov}} = 0.1$, this value is a factor of $\sim 20$ less than the accretion rate of the system. However, we caution that these candidates need to be confirmed with future observations. The lack of corresponding oxygen absorption is a problem at present.

We do not find positive evidence for a dusty warm absorber. The spectrum of MR 2251−178 allows us to set upper limits of $N_{\text{C}} \approx 2 \times 10^{19} \text{ cm}^{-2}$ and $N_{\text{O}} \approx 9 \times 10^{19} \text{ cm}^{-2}$, if dusty material is present in the nucleus of MR 2251−178.

We find changes in the absorption structure of MR 2251−178 during the observation, which is not accompanied by changes in the observed continuum luminosity. Possibly, we see nonequilibrium effects in the ionization of the gas responding to previous changes in luminosity or changes in density; the true mechanism can only be uncovered with deeper follow-up observations.

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