REVEALING THE DUSTY WARM ABSORBER IN MCG–6-30-15 WITH THE CHANDRA HETG

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ABSTRACT

We present detailed evidence for a warm absorber in the Seyfert 1 galaxy MCG–6-30-15 and dispute earlier claims for relativistic O line emission. The HETG spectra show numerous narrow, unresolved (FWHM ≤ 200 km s\(^{-1}\)) absorption lines from a wide range of ionization states of N, O, Mg, Ne, Si, S, Ar, and Fe. The O \(\text{VII}\) edge and 1s\(^2\) − 1s\(^n\)p resonance line series to \(n = 9\) are clearly detected at rest in the AGN frame. We attribute previous reports of an apparently highly redshifted O \(\text{VII}\) edge to the 1s\(^2\) − 1s\(^n\)p (\(n > 5\)) O \(\text{VII}\) resonance lines, and a neutral Fe L absorption complex. The shape of the Fe L feature is nearly identical to that seen in the spectra of several X-ray binaries, and in laboratory data. The implied dust column density agrees with that obtained from reddening studies, and gives the first direct X-ray evidence for dust embedded in a warm absorber. The O \(\text{VIII}\) resonance lines and weak edge are also detected, and the spectral rollover below ~ 2 keV is explained by the superposition of numerous absorption lines and edges. We identify, for the first time, a KLL resonance in the O \(\text{VI}\) photoabsorption cross section, giving a measure of the O \(\text{VI}\) column density. The O \(\text{VII}\) (f) emission detected at the systemic velocity implies a covering fraction of ~ 5% (depending on the observed vs. time-averaged ionizing flux). Our observations show that a dusty warm absorber model is not only adequate to explain all the spectral features ≥ 0.48 keV (≤ 26 Å) the data require it. This contradicts the interpretation of Branduardi-Raymont et al. (2001) that this spectral region is dominated by highly relativistic line emission from the vicinity of the black hole.

Subject headings: galaxies: active; quasars: general; X-ray: general; individual MCG–6-30-15

1. INTRODUCTION

Recently, workers analyzing the XMM-Newton RGS data of the luminous (L\(_X\) ~ 10\(^{43}\) erg s\(^{-1}\)) nearby (z=0.0078) Seyfert 1 galaxy MCG–6-30-15 and the similar object Mrk 766 have proposed a radical alternative to the warm absorber model as the origin of the spectral features in the soft (< 2 keV) band (Branduardi-Raymont et al. 2001, hereafter BR2001). It had been generally accepted that the features were imposed by partially ionized absorbing material at ≳ parsec distances from the black hole. The main signatures are strong O \(\text{VII}\) and O \(\text{VIII}\) absorption edges (e.g. Fabian et al. 1994), which are nearly ubiquitous in Seyfert 1 galaxies (e.g. Reynolds 1997, George et al. 1998). However, BR2001 propose that in MCG–6-30-15 and Mrk 766 the observed spectral features are soft X-ray emission lines from close to the black hole highly broadened by relativistic effects. This scenario is invoked to explain the apparent 16,000 km s\(^{-1}\) redshifted O \(\text{VII}\) edge without associated resonance lines.

Our Chandra High Energy Transmission Grating (HETG) observation does not support this interpretation. We present strong evidence for partially ionized absorbing material along the line of sight. In particular, we find absorption lines from a myriad of species in a range of ionization states which can explain the observed spectral rollover at the energies of the warm absorber. We demonstrate that the apparent redshifted O \(\text{VII}\) edge can be explained by the 1s\(^2\) − 1s\(^n\)p (for \(n ≥ 5\)) O \(\text{VII}\) resonance lines and a complex of Fe L edges, plausibly from dust in the ionized absorber. Here we concentrate on this evidence and leave more comprehensive analyses to subsequent publications.

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(2–5, 6.5-8, keV) HEG data simultaneously obtaining $\Gamma \approx 1.84$ for the time-averaged (120 ks) spectrum. The MEG energies 0.7–2.5 keV are excluded from our fits in order to mitigate the effect of the excess absorption in that energy range; the Fe K region is also excluded. (This is consistent with the best fit RXTE $3-10$ keV $\Gamma = 1.92 \pm 0.04$.) The source varied by ~50% during each observation. Correlated continuum flux and line strength variations were noted by Otani et al. (1996) with ASCA. Accordingly, we separated our data into ‘high’ and ‘low’ states arbitrarily defined as above and below our mean 2 cts s$^{-1}$. We concentrate our study of the warm absorber on the high state because many of the oxygen resonance absorption lines appear most prominent during this state.

3.1. Evidence for warm absorption

A strong testament to the existence of the warm absorber is the myriad of ionized species in the 0.5–1 keV range, and in particular resonance lines from N VII, O (VII, VIII), Ne (IX,X), Fe XVII to Fe XXI (Fig 1a). There are also many absorption lines of higher ionization states of Fe up to Fe XXIII, Mg, Si, S, Ar, and possibly Ca dispersed through the 0.9–5 keV bandpass. These lines, and the associated edges can plausibly account for the observed spectral ‘rollover’ $\lesssim 2$ keV.

Of particular note are the resonance lines O VII 1s$^2$−1sp and O VIII Lyα, Lyβ. We detect O VII 1s$^2$−1sp up to $n = 9$ with confidence levels from 95% to 99.9%. These lines, like all the absorption lines discussed in this paper are unresolved (implying FWHM $\lesssim 200$ km s$^{-1}$), and at the expected wavelengths to within $\lesssim 200$ km s$^{-1}$ (< 0.01 Å) which is within the HETG calibration uncertainty. The equivalent widths in the high state for $n = 2, 4, 6$–9 are respectively 17 ± 9 (0.45 eV), 13 ± 4 (0.51 eV), 12 ± 4, 11 ± 4, 12 ± 4, 13 ± 4 mÅ (the $n = 3, 5$ lines are confused with the N VII edge and the Fe L3 feature, respectively). Clearly these lines are on the flat part of the curve of growth. We performed a curve-of-growth analysis for trial sets of the parameters turbulent velocity $b$ and column $N_{OVII}$ (using the program described in Pettini et al. 1983, Mar & Bailey 1995) and find the minimum column density implied by the absorption lines is $N_{OVII} \approx 7 \times 10^{17}$ cm$^{-2}$ ($b \sim 100$ km s$^{-1}$) which requires an optical depth $\tau_{OVII} > 0.2$ at the O VII edge (Daltabuit & Cox 1972). Indeed, Fig. 1a shows an edge at 0.74 keV (16.8 Å), the energy expected for O VII at rest in the AGN frame. The drop across the edge implies $\tau_{OVII} \sim 0.6$–0.8, or $N_{OVII} \approx 2.5 \times 10^{18}$ cm$^{-2}$, which can account for the observed strengths of the O VII absorption series for $b \sim 100$ km s$^{-1}$, consistent with the lines being unresolved in our data. The O VIII edge is not strong in our data ($\tau_{OVIII} \approx 0.15 \pm 0.10$), and is complicated by a complex of nearby lines from Fe XVII and Fe XVIII species as well as the Ne IX 1s$^2$−1s2p resonance feature (e.g. Nicastro et al. 1999) shown in Fig. 1a. We find consistency between the O VIII Lyα and Lyβ equivalent widths (respectively 23 ± 5 mÅ [0.79 eV] and 19 ± 5 mÅ [0.92 eV]), and O VIII edge for $\tau_{OVIII} \sim 0.1$, or $N_{OVIII} \approx 1 \times 10^{18}$ cm$^{-2}$, and $b \sim 100$ km s$^{-1}$.

We now investigate the strong drop at $\sim 0.7$ keV (if this is the O VII edge, then its redshift is $\sim 16,000$ km s$^{-1}$ - e.g. BR2001), and spectral features which govern the O VII complex of lines by computing line strengths for the O VII ($2 \leq n < \infty$) resonance series. We use the line list of Verner et al. (1996) for the $n \leq 10$ oscillator strengths and wavelengths, and extrapolate using the hydrogenic approximation $f_n \propto 1/n^2$, for $n > 10$. We take the observed $\tau_{OVII} \sim 0.7$, and generate the theoretical spectral showing close up in Fig. 1b (for $b = 100$ km s$^{-1}$). It can be seen that the apparent redshift of the O VII edge is partially explained by the O VII $n > 5$ resonance series. We propose that both the $\sim 2500$ km s$^{-1}$ wide feature and residual absorption which cannot be explained by the O VII resonance series are due to the L edges of neutral iron. The Fe L3 edge at 0.707 keV (17.5 Å) and the associated Fe L2 edge seen in X-ray binaries (e.g. X0614+011, Paerels et al., 2001; Cyg X1, Schulz et al., 2001; for laboratory data, see Crocombe & Pollak 1995) show structure similar to that seen here. To illustrate, Fig 1b displays the MEG spectra of MCG–6–30–15 (de-redshifted) and Cyg X1 (suitably scaled) in this region. The agreement is remarkable, with most of the differences accounted for by the O VII edge and series absorption. The drop at 0.707 keV implies a neutral Fe column density of $\sim 4 \times 10^{17}$ cm$^{-2}$ or $N_{HF} \sim 4 \times 10^{13}$ cm$^{-2}$ for solar abundances, but as noted in §4, it is plausible to attribute the Fe to dust in the warm absorber, in which case most of the remaining elements are ionized. One does expect other features, the most prominent being O (Cyg X-1 also shows weak Si and Mg features which would not be detectable in our spectrum). Using the dust in Galactic halo clouds as a guide (Sembach & Savage 1996, Savage & Sembach 1996, argue for a population of oxides and perhaps pure iron grains) suggests O/Fe $\sim 1$–4 (cf., Snow & Witt 1996). An associated O I edge at the AGN redshift may be present in our spectrum but is confused by the instrumental O I edge which has not yet been fully calibrated. (BR2001 report an unspecified excess O absorption.)

We attribute the unresolved absorption line at 0.243 ± 0.004 Å (0.562 keV; Fig. 1a), detected at $\approx 99.9\%$ confidence in the full observation, to the strongest KLL resonance (photoexcitation to a doubly excited state followed by auto-ionization) in the photoabsorption cross section for O VI as recently calculated by Pradhan (2000). The MEG easily separates this feature (which is itself an unresolved doublet) from the nearby O VII forbidden line at 22.09 Å (561 eV) discussed below, giving an O VI equivalent width of 29 ± 8 mÅ (0.74 eV). Using Pradhan’s effective oscillator strength of 0.58 for this feature (assuming no radiative damping and $b \sim 100$ km s$^{-1}$) gives $N_{OVI} \sim 3 \times 10^{17}$ cm$^{-2}$. (An associated O I edge at 0.698 keV [17.76 Å] is too weak to be seen in our data.)

We have made a first attempt at modeling the spectrum of MCG–6–30–15. While not definitive, our model does explain the overall shape and most of the absorption features. In addition to the $\Gamma \sim 1.9$ power-law, we require a soft component and absorption by two ionized zones and neutrals in dust. At least two zones are needed to explain the wide range in ionization states that we observe from the absorption species. (Multiple zones were also previously suggested for MCG–6–30–15 by Reynolds et al. 1995, Otani et al., 1996, Morales, Fabian, & Reynolds 2000.) In addition to the two ionized zones, we add an extra column of $3.5 \times 10^{17}$ cm$^{-2}$ of FeO. We used the FeII cross sections provided by Kortright & Kim (2000), and O I cross section from Henke et al. (1982). A neutral Fe:O ratio of 1:2 is supported by the data, and is consistent with dust composed of Fe oxides or olivine (Fe3SiO4). The Si edge would not be detectable in our data. We did not attempt to model the O VII component. We calculate ionization fractions and the absorption spectrum of Fig. 1 for the two ionized zones using the photoionization code CLOUDY (Ferland 1998), the complete O VII resonance series, and the Verner et al. (1996) resonance line list, for the relevant species. The input parameters to CLOUDY assume a...
Galactic absorbed power-law ionizing continuum with \( \Gamma = 1.9 \), luminosity \( 10^{43} \text{ erg s}^{-1} \), and \( b = 100 \text{ km s}^{-1} \). Emission from recombination or resonance scattering is ignored (see below). The low and high ionization zones are respectively (log\( \xi \)=0.7; log\( N_{H} \) = 21.7), and (log\( \xi \)=2.5; log\( N_{H} \) = 22.5), where \( \xi = L/nR^{2} \). The model includes a 10% scattered continuum.

The multi-component warm absorber introduces an accumulation of absorption lines and edges (in particular various stages of Fe, Ne, Mg) which causes the spectrum to roll over below 2 keV. A soft excess is required to compensate for this absorption at energies < 0.7 keV. If it were not for the absorption, a single power-law with Galactic absorption could roughly account for the flux below 0.7 keV and above 2 keV. Our data cannot distinguish between a power-law of \( \Gamma \sim 2 \) or a 0.13 keV thermal black body for the soft excess. (However, a 0.13 keV blackbody would imply a mass for MCG–6-30-15 < \( 10^{8}M_{\odot} \), which is implausible).

3.2. \( \text{O VII (f) emission & possible filling-in of absorption lines} \)

We detect the \( \text{O VII} \ 1s2p^{3}S–1s^{2}S_{1} \) (forbidden) emission line at \( \lambda = 22.09 \pm 0.005 \text{ Å} \) (561 eV) with \( >99.9\% \) confidence and equivalent width \( 86 \pm 27 \text{ mÅ} \) (2.2 eV) for the combined observation. This line is particularly strong in photoionized plasmas and is unaffected by resonance scattering, so it is a good measure of the total rate of \( \text{O VII} \) recombination (and therefore photoionization) at the source. We can obtain an estimate for the covering factor \( f_{\text{cov}} \) of the \( \text{O VII} \) absorber by comparing the \( \text{O VII (f)} \) flux with the ionization rate along the line-of-sight for \( n_{\text{DVR}} \sim 0.7 \). Taking a branching ratio for \( \text{O VII (f)} \) of \( \sim 0.5 \) per recombination (computed for \( \sim 2 \times 10^{5} \text{ K} \), following Porquet & Dubau 2000, and Mewe & Gronenschild 1981), we find \( f_{\text{cov}} \sim 0.05R \), where \( R \) is the ratio of the \( \text{O VII} \) ionizing flux averaged over the light-travel time across the warm absorber region to the flux averaged over our observation.

The presence of \( \text{O VII (f)} \) emission must be accompanied by \( \text{O VII} \ 1s2p^{1}P–1s^{2}S_{1} \) resonance (r) line emission which could partially fill in the corresponding absorption line at 21.6 Å (574 eV). The (r)/(f) ratio from recombination is \( \sim 0.28 \) (Porquet & Dubau 2000) implying an equivalent width of \( \sim 20 \text{ mÅ} \) in (r). In addition to recombination, re-emission (and possibly cascades) following resonance absorption can also fill in some of the resonance lines. The actual amount of filling in from such resonance scattering is strongly dependent on geometry and radiative transfer. In any case, neglecting it strengthens our arguments for lower limits to the ion column densities based on the resonance absorption lines. From the \( \text{O VII (f)} \) line we estimate for \( \sim 2 \times 10^{5} \text{ K} \) (using Nahar 1999 and Porquet & Dubau 2000) that the equivalent width of the radiative recombination (bound-free) continuum from \( \text{O VII} \) is \( \sim 2 \text{ eV} \) with a likely width of \( \gtrsim 10 \text{ eV} \), so it would not be prominent in our data.

4. DISCUSSION

BR2001 concluded that their \textit{XMM-Newton} RGS observation of MCG–6-30-15 was “physically and spectroscopically inconsistent” with “standard” warm absorber models. The thrust of their argument is the inconsistency between the apparent highly redshifted \( \text{O VII} \) and \( \text{O VIII} \) edges and the absence of corresponding resonance absorption lines, which would be expected for any but the most contrived kinematic models. The same conclusion is reached for the similar spectrum of Mkn 766. They then propose that the spectra of both sources be explained by strong, highly relativistically broadened Ly \( \alpha \) emission lines of H-like O, N and C from the near vicinity of a Kerr black hole. This model implies that the rollover in the continuum below \( \sim 2 \text{ keV} \) is due to a \( \Gamma \sim 2.0 \) to \( \Gamma \sim 1.3 \) break in the power-
law. The absorption lines they detect are attributed to low column density absorbers with turbulent velocities $\sim 2000 \text{ km s}^{-1}$ FWHM; note that such velocities would be easily resolved in our spectra, which have $\gtrsim 3$ times better resolution, but are not seen.

Our Chandra HETG spectrum of MCG–6–30–15 shows that a dusty warm-absorber model is not only adequate to describe all the spectral features $\gtrsim 0.48 \text{ keV (} \lesssim 26 \text{ Å})$, the data require it. Firstly, we observe an abundance of highly-ionized resonance lines from a myriad of species in a range of ionization states (from O vi to Si xiii to Fe xxiii). The complex of these absorption features and associated edges will cause the spectrum to roll over at $< 2 \text{ keV}$, but also to partially recover at lower energies. Secondly, we detect the O vii $1s^2 - 1snp(n = 2 - 9)$ resonance absorption lines at the expected positions for absorbing material at rest in the AGN frame. The roughly comparable strengths of these lines indicate an O vii edge opacity of at least $\tau_{\text{O vii}} > 0.2$. The value $\tau_{\text{O vii}} \approx 0.7$ indicated by the discontinuity at the edge (at rest in the AGN frame) is fully consistent with the line strengths for $b \sim 100 \text{ km s}^{-1}$. Thirdly, we show that the apparent highly redshifted O vii edge which prompted the BR2001 interpretation can be explained in the context of a warm absorber. We propose that it is partly due to the expected redward shift of the absorption edge by the overlapping O vii $1s^2 - 1snp$, $n > 5$ series of absorption lines, and partly to an Fe L edge complex from a significant column density of neutral Fe. The shape of this complex is remarkably similar to that seen in the MEG data of Cyg X–1 (Fig. 1b, Schulz et al. 2001). A strong O viii line is not seen in our data, however a small edge is fully consistent with the observed O viii Ly $\alpha$ and Ly $\beta$ absorption lines. Previous reports of a redshifted O viii edge can be attributed to the series of Fe and Ne lines near 0.87 keV (14.2 Å) which could mimic a broadened/shifted edge. Our first attempts to model the full spectrum also require an additional soft emission component, but this should be broad (e.g., a steep power law or black body). Of course, we cannot rule out some small contribution from relativistically broadened emission lines as well, and our data cannot address the shape of the spectrum below 0.48 keV. However, since we see no evidence for such line emission and can explain the great many features we do see as coming from a dusty warm absorber, we conclude that the BR2001 interpretation of a spectrum dominated by relativistic line emission is no longer tenable.

The most plausible explanation of the Fe I L feature is absorption by dust that is embedded in the partially ionized material. [Grain survival in the dusty warm absorber of MCG–6–30–15 is addressed by Reynolds et al. (1997).] Otherwise, for cosmic abundances the implied neutral column density, $N_H \sim 4 \times 10^{21} \text{ cm}^{-2}$, would extinguish the X-ray spectrum at low energies, contrary to the observations. The presence of dust in the warm absorber of MCG–6–30–15 was already identified by Reynolds et al. (1997) based on the optical reddening of $E(B-V) = 0.61 - 1.09$, which implies $N_H \approx 4 - 7 \times 10^{21} \text{ cm}^{-2}$ (Cox 1999). Our independent measurement based on the Fe L absorption is consistent with this value. Therefore the presence of neutral absorption is not only explained, it is required by the observed reddening. (Dusty warm absorbers have been suggested for other AGN as well [e.g. Brandt, Fabian, & Pounds 1996, Reynolds 1997, Komossa 2000; see also Mathur 1994].) This first detection of a spectral feature attributed to the dust in an ionized absorber provides a new probe of this component. The shape of the Fe L features and the detection or limits on other absorbing species may eventually constrain the chemical composition of the grains. We note that Mrk 766 (BR2001) also shows optical/UV extinction (Walter & Fink 1993) suggesting that the above explanation for MCG–6–30–15 may also apply.

We believe that our detection of an O vi photoabsorption KLL resonance is the first time such a feature has been detected in the X-ray band (possibly including in the laboratory). It has two important implications. First, it shows that even relatively low ionization states previously detectable only in the UV can be studied in detail in the X-ray band. Second, it underscores the importance of having detailed calculations of the complex resonant structure in the photoabsorption cross sections of highly ionized species. Recent calculations show great complexity (e.g. Nahar 1999, Zhang & Pradhan 1999, Pradhan 2000) that has not yet been incorporated into the models of warm absorbers.

The estimate of $\sim 5 \%$ placed on $f_{\text{cov}}$ by the strength of the O vii (f) emission suggests that the observed luminosity of the nucleus is $\gtrsim$ its average over the light-travel time across the O vii region (years, see Otani et al. 1996) else $f_{\text{cov}}$ would be implausibly small.

These observations, and other recent work on AGN with Chandra and XMM-Newton (e.g. Kaastra et al. 2000, Kaspi et al. 2000, Ogle et al. 2000, Sako et al. 2001a, b) illustrate the enormous power of high resolution spectroscopy to probe the detailed physics of the ionized region in AGN. They also show the complexity of these regions, as anticipated by Netzer (1993), Nicastro (1999), Porquet & Dubau (2000) and others. For example, our data imply that the MCG–6–30–15 absorber spans a wide and possibly continuous range of ionization, with embedded dust that will introduce complex absorption features and also affect the state of the plasma. Resonance scattering and cascades are also likely to be important, as is recombination line emission, as indicated by the detection of O vii (f). The absorbing region may also be a source of thermal line emission, as seen in the HETG observation of NGC 4151 (Ogle et al. 2000). We intend to pursue these issues in future publications.

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