The Chandra High Energy Transmission Grating Spectrometer probes the DUSTY WARM ABSORBER in the Seyfert 1 galaxy MCG–6-30-15

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The Chandra HETGS spectra of the Seyfert 1 galaxy MCG–6-30-15 show numerous narrow, unresolved (FWHM \(\lesssim 200\) km s\(^{-1}\)) absorption lines from a wide range of ionization states of N, O, Mg, Ne, Si, S, Ar, and Fe. The initial analysis of these data, presented in Lee et al. (2001), shows that a dusty warm absorber model adequately explains the spectral features \(\gtrsim 0.48\) keV (\(\lesssim 26\) Å). We attribute previous reports of an apparently highly redshifted O\(\text{vii}\) edge to the neutral Fe L absorption complex and the O\(\text{vii}\) resonance series (by transitions higher than He\(\gamma\); He\(\alpha,\beta,\gamma\) are also seen at lower energies). The implied dust column density needed to explain the Fe L edge feature agrees with that obtained from earlier reddening studies, which had already concluded that the dust should be associated with the ionized absorber (given the relatively lower observed X-ray absorption by cold gas). Our findings contradict the interpretation of Branduardi-Raymont et al. (2001), based on XMM-Newton RGS spectra, that this spectral region is dominated by highly relativistic soft X-ray line emission originating near the central black hole. Here we review these issues pertaining to the soft X-ray spectral features as addressed by Lee et al., (2001). Details found in Lee et al., 2001, ApJ., 554, L13 [1]

1. Introduction

Recently, workers analyzing the XMM-Newton RGS data of the luminous (\(L_x \sim 10^{45}\) 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 (\(\lesssim 2\) keV) band (Branduardi-Raymont et al. 2001 [2], hereafter BR2001). It had been generally accepted that the features were imposed by partially ionized absorbing material at \(\gtrsim 26\) parsec distances from the black hole. The main signatures are strong O\(\text{vii}\) and O\(\text{viii}\) absorption edges, which are nearly ubiquitous in Seyfert 1 galaxies. However, BR2001 proposed 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 on top of a very flat continuum. This scenario was 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 Spectrometer (HETGS) observation does not support this interpretation – it shows that a warm absorber model, with the addition of a contribution from dust, can describe the spectrum of MCG–6-30-15. The main points of the arguments presented in Lee et al., (2001) [1] are reiterated here, and the reader is referred to that paper for details. The MCG–6-30-15 luminosity, assuming \(H_0 = 50\) km s\(^{-1}\) Mpc\(^{-1}\) is \(L_x \sim 1.3 \times 10^{43}\) erg/s for the flux state reported in our paper. In contrast, the flux of MCG–6-30-15 during the epoch of the XMM-Newton look presented by BR2001 is comparable to the ‘deep minimum’ studied by Iwasawa et al., (1996) [3]. The best fit Galactic (\(N_H \sim 4 \times 10^{20}\) cm\(^{-2}\)) absorbed power-law to the Chandra data is \(\Gamma \sim 1.9\) consistent with simultaneous RXTE observations (e.g. Fig. 1).

2. Evidence for Warm Absorption : Dust vs. GR

BR2001 concluded that their XMM-Newton RGS observation of MCG–6-30-15 was “physically and spectroscopically inconsistent” with “standard” warm absorber models. Our Chandra HETGS spectrum of this source shows that a dusty warm-absorber model is not only adequate to describe the spectral features \(\gtrsim 0.48\) keV (\(\lesssim 26\) Å), the data require it. We detail below the primary criticisms of the BR2001 model as presented in the Lee et al., (2001) paper. We note that at the time of writing, the BR2001 model is the only model presented for the XMM-Newton data of MCG–6-30-15 for which details are published or in preprint form.
The thrust of the BR2001 argument

Our hole on top of a much flatter continuum.

...and C from the near vicinity of a Kerr black tically broadened Ly emission lines of H-like O, N and C from the near vicinity of a Kerr black hole.

In order to reconcile this apparent inconsistency, they propose that the spectra of MCG–6-30-15 (and Mkn 766) be explained by strong, highly relativistically broadened Ly α emission lines of H-like O, N and C from the near vicinity of a Kerr black hole on top of a much flatter continuum.

(1) XMM: The thrust of the BR2001 argument is the inconsistency between the apparent highly redshifted O vii (by ~16,000 km s⁻¹) and O viii edges and the absence of corresponding resonance absorption lines, which would be expected for any but the most contrived kinematic models. In order to reconcile this apparent inconsistency, they propose that the spectra of MCG–6-30-15 (and Mkn 766) be explained by strong, highly relativistically broadened Ly α emission lines of H-like O, N and C from the near vicinity of a Kerr black hole.

Figure 1. A simple power-law of Γ ≈ 1.9 modified by Galactic (N_H = 4.06 × 10²² cm⁻²) absorption fits the MEG and HEG data well. The 0.7-2.5 keV region are excluded from our fits in order to mitigate the effects of excess absorption in that energy range. The 6.5–8 keV iron region is also excluded.

(1) Chandra: Our Chandra data shows that the apparent highly redshifted O vii edge which prompted the BR2001 interpretation can be explained by a warm absorber, with dust. Fig. 3 shows that this region can be well explained by a neutral Fe L edge with a significant (equivalent N_H ~ 4 × 10²¹ cm⁻²) column density in congruence with the overlapping O vii 1s²−1snp, n ≥ 5 series (i.e. He δ to the series limit) of absorption lines which carves away at the spectrum redward of the O vii edge (i.e. between ~ 0.70 and 0.74 keV).

The Fe I L III (and L II) edge features are particularly significant. The most plausible explanation for this feature is absorption by dust that is embedded in the partially ionized material; consequently the bulk of the gas is ionized. Otherwise, for the column densities (N_H ~ 4 × 10²¹ cm⁻²) implied by the drop across the ~0.7 keV Fe L III edge, the soft spectral features would be absorbed. [We note that the Fe L III edge at 0.707 keV (17.5 Å) and the associated Fe L II edge show structure similar to that seen seen in X-ray binaries (e.g. X0614+011 and Cyg X-1, respectively [8, 9], and measured recently in the labo-

Table 1: † oscillator strength, a confused – near N vii edge, b confused – near Fe L III, L II edge
The absorption lines detected by Indeed an O
Since we do not know the de-
The BR2001 model, as published, im-
e.g. 1–4 correspond to 1s
\(2\) to the transitions (i.e. 1s
the warm absorber. The labels ‘1–
0.74 keV to 0.70 keV) is explained by the O
\(n \geq 3\), which implies
absorber of MCG–6-30-15 (black) shows that the ap-
other similar AGN (e.g. [7, 8], and references
not the first time that dust has been proposed as
\(\sim 1000\) km/s would correspond to a line width
\(\sim 2000\) km s\(^{-1}\) FWHM which they claim is insuffi-
(2) Chandra : Indeed an O \(\text{vii}\) edge would not be
detectable IF the O \(\text{vii}\) column densities are the
low values quoted by BR2001. However, Table 1
shows that we detect the O \(\text{vii}\) series from He \(\alpha\)
\(n = 1\) to He \(\eta\) \((n = 9)\). The comparable values
of the equivalent widths of these lines for oscilla-
tor strengths \((f_{ij})\) which differ by \(\sim\) couple orders
of magnitude (e.g. between the \(n = 1\) and \(n = 9\)
O \(\text{vii}\) series) imply that they are on the flat part
of the curve of growth (Table 1). Accordingly,
we performed a curve-of-growth analysis and esti-
mate the minimum column density implied by the
absorption lines to be \(N_{\text{OVII}} \geq 7 \times 10^{17}\) cm\(^{-2}\) (for
turbulent velocity width \(b \sim 100\) km s\(^{-1}\)) which
requires an optical depth \(\tau_{\text{OVII}} > 0.2\) at the O \(\text{vii}\)
edge. This is consistent with the actual drop
across the O \(\text{vii}\) edge at 0.74 keV (16.8 \(\AA\)) which
gives \(\tau_{\text{OVII}} \sim 0.6–0.8\), or \(N_{\text{OVII}} \approx 2.5 \times 10^{18}\) cm\(^2\).
These column densities are \(\approx 1–2\) orders of
magnitude greater than that quoted by BR2001.
These are not resolved in the \textit{Chandra} HETGS.
We note that the \textit{Chandra} resolution in this
region is FWHM \(\sim 0.023\) \(\AA\) (compared to the
\textit{XMM-Newton} resolution of \(\sim 0.06\) \(\AA\)). A FWHM
of 2000 km/s would correspond to a line width
of 0.11\(\AA\) which we can clearly rule out with the
\textit{Chandra} data. To summarize, the \textit{Chandra}
data show a lower limit of \((N_{\text{OVII}} > 7 \times 10^{17}\) cm\(^{-2}\))
based on the detected O \(\text{vii}\) resonance lines (velocity
widths \(\lesssim 200\) km s\(^{-1}\)) in contrast to the order of
magnitude larger \(\sim 2000\) km s\(^{-1}\) widths quoted
by BR2001), and \(N_{\text{OVII}} \sim 2.5 \times 10^{18}\) cm\(^{-2}\) from
the discontinuity at the \(\sim 0.74\) keV O \(\text{vii}\) edge
(which is at zero velocity).

(3) XMM : The BR2001 model, as published, im-
plies that the rollover in the continuum below
\(\sim 2\) keV is due to a \(\Gamma \sim 2.0\) to \(\Gamma \sim 1.3\) break
in the power-law. We note, however, that as of
this meeting our understanding is that this model
is currently being revised.

(3) Chandra : Since we do not know the de-
tails of the revised model to explain the XMM-Newton data, we will address the published model as presented in the BR2001 paper. We note however that any model which allows for significant emission at the lower energies will require a suppression of the continuum. We believe the break implied in BR2001 is unphysical, especially since such a flat continuum lying under the soft X-ray disk-line violates the Comptonization argument for the hard X-ray emission [9]. Furthermore, we have shown that 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 (e.g. Fig. 1). An excess soft continuum (e.g. black-body or steep power-law) is required to compensate for this absorption at energies $< 0.7$ keV, as seen in many other AGN. 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 (Fig. 1).

2.1. Additional points to consider

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 we 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 unwarranted. We note below some additional points to consider.

- A strong testament to the existence of the warm absorber is the myriad of ionized species (e.g. Fig. 1a in Lee et al.). 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 (Lee et al., in preparation).

- Our Chandra spectra cannot be used to address the spectral features below 0.48 keV ($> 26 \AA$). Accordingly, we make a rough estimate of the Fe:O ratio in dust – while we believe it is reasonable, it may not be entirely appropriate for modeling the low energies (for e.g. the C absorption edge) to which our instrument is not sensitive. The exact shape of the soft excess will be important for properly modeling the composition of the dust in MCG–6-30-15, and needs further consideration. However, we stress that dust has to be included in any model of MCG–6-30-15. What remains is to deduce from the data its properties, and composition.

- As stated in Lee et al., the detection of the O vii (forbidden) emission in the Chandra spectra would necessitate that re-emission following resonance absorption can fill in some of the resonance lines, thereby making the absorption appear weaker than it actually is. It should be noted also that the amount of resonance re-emission in a clumpy warm absorber into our line of sight is entirely dependent on the geometry. This is well known from studies of stellar coronae, including that of the Sun. Accordingly, the scenario in which recombination cascades dominate over resonance re-emission will only apply for an isotropic absorber (uniformly filled sphere or slab) which is clearly an unwarranted geometry as demonstrated by the calculation based on the O vii (f) line in our paper. Photoexcitation was not addressed.

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