A CHANDRA HETGS SPECTRAL STUDY OF THE IRON K BANDPASS IN MCG −6-30-15:
A NARROW VIEW OF THE BROAD IRON LINE

A. J. Young,1 J. C. Lee,2,3 A. C. Fabian,4 C. S. Reynolds,5 R. R. Gibson,1 and C. R. Canizares1

Received 2005 February 7; accepted 2005 March 30

ABSTRACT

We present a high-resolution X-ray spectrum of the iron K bandpass in MCG −6-30-15 based on a 522 ks observation with Chandra’s High Energy Transmission Grating Spectrometer (HETGS). The Chandra spectrum is consistent with the presence of a relativistically broadened, highly redshifted iron Kα emission line with a profile similar to previous observations. A number of narrow features are detected above 2 keV, including a narrow Fe Kα emission line and narrow absorption lines from H- and He-like Fe, H-like S, and H-like Si. This absorption is well described by a photoionized plasma with a column density log NH = 23.2 and an ionization parameter log ξ = 3.6, assuming the iron abundance has the solar value and a velocity dispersion parameter b = 100 km s−1. Applying this absorption model to a high-fidelity XMM-Newton EPIC pn spectrum, we find that a broad iron line is still required with emission extending to within 1.9rg of the black hole. If the iron line comes from an accretion disk truncated at the innermost stable circular orbit, this indicates that the black hole must be spinning rapidly with a > 0.95. Ionized absorption models attempting to explain the 3–6 keV spectral curvature without strong gravity predict absorption lines in the 6.4–6.6 keV range that are inconsistent with the Chandra spectrum. The H- and He-like iron absorption lines in the Chandra spectrum are blueshifted by 2.0+0.7 −1.0 × 103 km s−1 compared to the source frame and may originate in a high-velocity, high-ionization component of the warm absorber outflow. This high-ionization component may dominate the energy budget of the outflow and account for a significant fraction of the outflowing mass. Detailed modeling of the warm absorber below 2 keV will be addressed in a later paper, but our results are robust to the broader details of the warm absorber behavior. The difference spectrum between the high- and low-flux states is well described by a power law, in agreement with previous studies.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active —
galaxies: individual (MCG −6-30-15) — galaxies: Seyfert — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

Efficiently accreting black holes are prodigious sources of X-rays. The illumination of a dense thin accretion disk with X-rays inevitably leads to the production of a strong iron fluorescence line (Fabian et al. 1989; Nandra et al. 1989). If the accretion disk lies deep in the potential well of the black hole, the fluorescent iron line profile will be broadened and skewed in a characteristic manner by the Doppler and transverse Doppler shifts of the high-velocity orbiting gas and the gravitational redshift and light focusing of the black hole (see, e.g., the review articles by Fabian et al. 2000; Reynolds & Nowak 2003). As such, the broad iron line is potentially a powerful probe of the astrophysics and spacetime in the immediate vicinity of a black hole. A major Advanced Satellite for Cosmology and Astrophysics (ASCA) discovery was just such a line at 6.4 keV from Fe Kα in the Seyfert 1 galaxy MCG −6-30-15 (Tanaka et al. 1995), which showed broadening as large as ~100,000 km s−1. Subsequent studies of other active galactic nuclei (AGNs) have reinforced the existence of broad lines ( Mushotzky et al. 1995; Nandra et al. 1997).

The broad iron line in MCG −6-30-15 has been extensively studied with ASCA (Iwasawa et al. 1996, 1999; Shih et al. 2002), BeppoSAX (Gualandris et al. 1999), the Rossi X-Ray Timing Explorer (RXTE: Lee et al. 1999, 2000; Vaughan & Edelson 2001), the Chandra X-Ray Observatory (Lee et al. 2002b) and the X-Ray Multi-Mirror mission (XMM-Newton: Wils et al. 2001; Fabian et al. 2002; Vaughan & Fabian 2004; Reynolds et al. 2004). All observations are consistent with a broad, highly redshifted disk line feature. Most alternative mechanisms for broadening the iron emission line (i.e., those that do not require strong gravity) are unlikely to work (e.g., Fabian et al. 1995; Reynolds & Wilms 2000; Ruszkowski et al. 2000). We present a deep Chandra High Energy Transmission Grating Spectrometer (HETGS) observation of MCG −6-30-15 and, concentrating on the iron K bandpass, describe the narrow emission and absorption features in the spectrum above 2 keV, constrain the column densities and ionization parameters of highly ionized absorbing gas, and discuss the implications. We investigate whether the broad iron line is not an emission feature but the result of a curved continuum spectrum caused by ionized absorption (e.g., Kinkhabwala 2003). Detailed modeling of the warm absorber below 2 keV will be addressed in a later paper, and our results are robust to the broader details of the warm absorber behavior.

2. OBSERVATIONS

MCG −6-30-15 (z = 0.007749) was observed by the Chandra HETGS between 2004 May 19 and 27 (obs/4759, obs/4760, obs/4761, and obs/4762), resulting in a good exposure time of
522 ks. Spectra and instrument responses were generated using the standard CIAO tools and analyzed using the ISIS spectral fitting software (Houck 2002). For improved accuracy, we correct the individual S0–S5 chip effective areas (ancillary response functions [ARFs]) before combining them to generate the medium-energy gratings (MEG) and high-energy gratings (HEG) +1 and −1 effective areas used for data analysis. To do so, we correct the quantum efficiencies (QEs) of the S0, S2, S4, and S5 front-illuminated (FI) S1 and S3 chips using a publicly available correction factor (Marshall et al. 2004).6 The correction is <10% above 900 eV and <19% below. Once corrected, the CIAO tool dmarfadd was used to combine the S0–S5 effective areas to create the −1 and +1 ARFs. The +1 and −1 orders of the HEG were combined, as were the +1 and −1 orders of the MEG. The HEG and MEG spectra were modeled separately. The zeroth-order function [ARFs] before combining them to generate the medium-energy gratings (MEG) and high-energy gratings (HEG) +1 and −1 effective areas used for data analysis. To do so, we correct the quantum efficiencies (QEs) of the S0, S2, S4, and S5 front-illuminated (FI) S1 and S3 chips using a publicly available correction factor (Marshall et al. 2004). The correction is <10% above 900 eV and <19% below. Once corrected, the CIAO tool dmarfadd was used to combine the S0–S5 effective areas to create the −1 and +1 ARFs. The +1 and −1 orders of the HEG were combined, as were the +1 and −1 orders of the MEG. The HEG and MEG spectra were modeled separately. The zeroth-order spectrum is heavily piled up (≈90% given an observed zeroth-order rate of ≈0.7 counts per frame) and is not used. The combined HEG plus MEG first-order 0.45–10 keV count rate varies between ≈0.4 and 2 counts s−1, and the light curve is shown in Figure 1. The error bars quoted throughout the paper are the 90% confidence interval (Δν2 = 2.706 for one interesting parameter), unless explicitly stated otherwise.

2.1. Broad Iron Line

To show the broad iron line, the high-resolution HEG spectrum was heavily binned to 0.067 Å bin−1, and an absorbed power-law model was used to join the 2.25–2.5 and 7–7.5 keV bands (see Fig. 2). The best-fit photon index is Γ = 1.82 ± 0.05, with the neutral absorbing column density fixed at N_H = 2.1 × 10^{21} cm−2 to approximate the effects of the warm absorber (a few percent above ≈3 keV; Lee et al. 2001).

The broad iron line profile is very similar to that seen in previous observations, and a comparison between the Chandra and XMM-Newton (Vaughan & Fabian 2004) line profile is shown in Figure 3. The “red wing” of the iron K line extends from ≈6 keV down to ≈3–5 keV, and the “narrow core” peaks around 6.4 keV.

The broad iron line profile is very similar to that seen in previous observations, and a comparison between the Chandra and XMM-Newton (Vaughan & Fabian 2004) line profile is shown in Figure 3. The “red wing” of the iron K line extends from ≈6 keV down to ≈3–5 keV, and the “narrow core” peaks around 6.4 keV.
the normalization of the reflected spectrum to the normalization of the power law, with a value of 1 for an isotropic source above the disk is fixed at 2.2, and the iron abundance is fixed at 3 times the solar value based on previous XMM-Newton observations (Fabian et al. 2002). Both the reflection and iron line component are blurred by a disk line kernel for emission around a spinning Kerr black hole (Laor 1991), and everything is absorbed by a fixed neutral column density. In addition, a narrow, neutral Fe Kα line is added at 6.4 keV in the source frame to represent reflection off distant material, e.g., the narrow-line region or torus. The model parameters are given in Table 1.

The HETGS spectrum is best suited to studying narrow spectral features and does not strongly constrain the broad-line properties. A model in which the reflection fraction is fixed at $R = 1$ and the iron abundance fixed at the solar value also provides a good description of the spectrum with similar broad iron line parameters and an almost identical $\chi^2$/dof of 143/123. Since we cannot easily distinguish between such broadband models, we have adopted the values used by Fabian et al. (2002): i.e., $R = 2.2$ and an iron abundance of 3 times the solar value, and the line energies and equivalent widths (EWs) we measure are insensitive to this choice. We can, however, show that the HETGS spectrum is better described by a neutral broad iron line than an ionized broad iron line. If the iron line added to the reflection spectrum is at 6.7 keV instead of 6.4 keV, the best-fit model has a worse $\chi^2$/dof $= 152/123$. We do not include the weak reflection continuum associated with the narrow 6.4 keV line, and this does not affect our results.

### 2.2. Narrow Iron Line Components

The unbinned HEG spectrum (0.0056 Å bin$^{-1}$; the FWHM of the HEG is 0.012 Å) shows a number of narrow emission and absorption features in the iron K bandpass (Fig. 4). The 5.5–7.5 keV continuum and broad iron line were modeled as described in § 2.1 and Table 1, with most of the parameters fixed except the normalizations of the continuum and broad line and the parameters of the Gaussian representing the neutral Fe Kα line. Individual absorption lines were added as Gaussians with their centroids, strengths, and widths being free parameters. The best-fit line parameters are given in Table 2.

There is a narrow emission line at 6.39 keV (source frame), consistent with neutral iron Kα fluorescence, that has an EW of 18 eV (in good agreement with Lee et al. 2002b) and a FWHM of $<4700$ km s$^{-1}$. We also detect two unresolved absorption features, one at 6.69 keV (observed) consistent with the 1s$\rightarrow$2p resonance line of He-like iron (6.70 keV; Verner et al. 1996) and the second at 6.96 keV (observed) consistent with the two 1s$\rightarrow$2p resonance lines of H-like iron (6.95 and 6.97 keV; Verner et al. 1996). Both of these absorption features are consistent with zero redshift or, if associated with MCG$-6-30-15$, an outflow velocity of $2.0^{+0.7}_{-0.9} \times 10^7$ km s$^{-1}$ for Fe xxv and $1.9^{+0.7}_{-0.8} \times 10^3$ km s$^{-1}$ for Fe xxvi.

### 2.3. Variability

We now compare the spectrum of MCG $-6-30-15$ in a high- and low-flux state, since this can help determine whether certain spectral features are caused by absorption or emission. Using the combined first-order HEG plus MEG light curve of MCG$-6-30-15$ with 500 s bins (Fig. 1), we extracted high- and low-flux state spectra from those bins with count rates greater than or less than 1.2 counts s$^{-1}$, respectively. The effective exposure times are 172 ks for the high-flux state and 350 ks for the low-flux state, chosen so that the signal-to-noise ratio of each spectrum is comparable. The high- and low-flux state HEG spectra are shown in Figure 5, and the parameters of the narrow iron emission and absorption lines are given in Table 2. The line centroid energies are consistent between the high- and low-flux states. The difference in the continuum spectrum between the high- and low-flux states in the 2.25–7 keV band is well described ($\chi^2_\nu = 0.9$) by a power law of photon index $\Gamma = 2.0^{+0.1}_{-0.2}$ (see Fig. 6), in agreement with previous findings that the variability is dominated by a power-law component (e.g., Fabian et al. 2002; Turner et al. 2003; Fabian & Vaughan 2003; Vaughan & Fabian 2004). Furthermore, there is no evidence of continuum curvature or systematic deviation from a power-law.

![Figure 4](link)
from a power-law model in the 2.25–7 keV band. A narrow He-like iron absorption feature is weakly detected at approximately 6.7 keV in the difference spectrum.

3. DISCUSSION

3.1. Column Densities

We can estimate the column densities of Fe xxv and Fe xxvi ions from the EWs of their absorption lines (see, e.g., Spitzer 1978; Kotani et al. 2000). The inferred column density depends on the absorption line profile, and we assume the absorber has a Maxwellian velocity dispersion with a velocity spread parameter \( b = \sqrt{2\sigma} \), where \( \sigma \) is the radial velocity dispersion. The thermal broadening is roughly \( b \approx 20 \text{ km s}^{-1} \) for reasonable temperatures, so larger values of \( b \) will imply some bulk motion or turbulence in the absorber(s). The column of Fe xxv required to produce an 18 eV EW absorption line is \( N_{\text{Fe xxv}} \approx (3 \times 10^{17}) \)–(3 \times 10^{18}) \( \text{cm}^{-2} \) for \( b = 500–100 \text{ km s}^{-1} \), respectively. Similarly, the column density of Fe xxvi required to produce a 21 eV EW absorption line is \( N_{\text{Fe xxvi}} \approx (6 \times 10^{17}) \)–(4 \times 10^{19}) \( \text{cm}^{-2} \) for \( b = 500–100 \text{ km s}^{-1} \), respectively. The corresponding hydrogen column density depends on the iron abundance and fraction of iron in each ionization state. For Fe xxv we estimate \( N_H \approx (0.5/X_{25}) \left( n_{\text{H Fe}}/3 \times 10^{4}/(2 \times 10^{22}) \right) \) cm\(^{-2} \) for \( b = 500–100 \text{ km s}^{-1} \), respectively, where \( n_{\text{H Fe}}/3 \times 10^{4} \) is the ratio of hydrogen ions to all iron ions (3 \times 10^{4} for solar abundance) and \( X_{25} \) is the fraction of iron ions found in Fe xxv (which peaks around 0.5). Similarly, for Fe xxvi we infer \( N_H \approx (0.5/X_{25}) \left( n_{\text{H Fe}}/3 \times 10^{4}/(4 \times 10^{22}) \right) \) cm\(^{-2} \) for \( b = 500–100 \text{ km s}^{-1} \), respectively. If the H- and He-like Fe absorption lines are produced in a single absorber with log \( \xi \approx 3.5–4 \), then \( X_{25} \approx X_{26} \approx 0.4–0.5 \) (see Fig. 8 of Kallman & Bautista 2001).

If we model the absorbing gas as a photoionized plasma illuminated by a power law using the XSTAR code (Kallman & Bautista 2001), with solar iron abundance and \( b = 100 \text{ km s}^{-1} \), a good fit (\( \chi^2 = 1.1 \)) to the 5.5–7.5 keV spectrum is given by a power law plus disk line plus narrow iron K\( \alpha \) emission line absorbed by a column density log \( N_H \approx 23.2^{+0.3}_{-0.6} \) with an ionization parameter log \( \xi \approx 3.6^{+0.1}_{-0.2} \) where \( \xi = L_{\text{ion}}/(n_e R^2) \), \( L_{\text{ion}} \) is
the 1–1000 Ryd luminosity, and $R$ is the distance between the continuum source and cloud. For 3 times solar abundance the column density drops to $\log N_{\text{H}} = 22.9^{+1.0}_{-1.0}$ The redshift of the absorbing gas is $z = 1.3^{+1.3}_{-1.1} \times 10^{-3}$. Note also that there is some degeneracy between the ionization parameter and $b$, since both can affect the ratio of Fe xxv EW to Fe xxvi EW. The best-fitting XSTAR model predicts other absorption features that are consistent with the *Chandra* HEG spectrum. The strongest lines predicted by the model in the energy range $2 \text{ keV} \leq E \leq 6 \text{ keV}$ are S xvi Ly$\alpha$ at 2.62 keV and Si xiv Ly$\alpha$ at 2.01 keV. Both of these absorption lines are detected in the HEG spectrum (Fig. 7; Table 2), with outflow velocities of $2288^{+687}_{-225}$ km s$^{-1}$ for S xvi and $224^{+820}_{-126}$ km s$^{-1}$ for Si xiv. We have not considered in our fit the spectrum below 2 keV or the warm absorber, which will be the subject of a future study. The column densities in the high- and low-flux states are statistically consistent with a single value equal to that of the time-averaged spectrum.

3.2. Robustness of the Broad Iron Line

It has been proposed that the extremely redshifted red wing of the iron K line might actually be caused by absorption (e.g., Kinkhabwala 2003). In this model the continuum passes through a large column density of moderately ionized gas, which causes significant curvature of the transmitted continuum above the iron L edge at $\sim 0.7 \text{ keV}$ that extends up to the iron K bandpass ($\geq 5 \text{ keV}$), and this curvature can mimic the red wing of the putative broad iron K$\alpha$ emission line. For iron to have L-shell electrons the absorbing gas cannot be as highly ionized as the gas giving rise to the H- and He-like iron absorption lines. On the other hand, the gas must be sufficiently highly ionized to avoid excessive opacity of soft X-rays; therefore, $\zeta \gtrsim 10–100$ (Krolik & Kallman 1984). The fact that the difference spectrum between the high- and low-flux states above 2.25 keV (where the effect of the warm absorber is small) is well described by an unabsorbed power law (§ 2.3) strongly suggests that the curvature is not an absorption artifact. If the curvature in the time-averaged hard X-ray spectrum is caused by an intervening absorber with constant optical depth, $\tau = N\sigma(E)$, then the absorption should affect the intrinsic high state, $F_h$, and intrinsic low state, $F_l$, similarly (i.e., as $e^{-\tau}F_h$ and $e^{-\tau}F_l$, respectively), and hence the difference spectrum should also show the same absorption [i.e., $e^{-\tau}(F_h - F_l)$].

We do not expect $\tau$ to vary between the high- and low-flux states, since the continuum variability timescale is so short (typically hundreds of seconds). Even though the difference spectrum does not show such an absorption signature above 2.25 keV, in this section we present a comparison between an absorption model and the *Chandra* HEG spectrum.

To test the ionized absorption hypothesis, we modeled the 3–10 keV *XMM-Newton* European Photon Imaging Camera (EPIC) pn spectrum (Vaughan & Fabian 2004) with an XSTAR model absorbing a power-law spectrum, excluding the 6–8 keV range in which the line has a more complicated profile and narrow core (see Fig. 3). The curvature of the broad red wing is approximately described by a model with solar iron abundance, $b = 100 \text{ km s}^{-1}$, $\log N_{\text{H}} = 22.6^{+0.1}_{-0.0}$, $\log \xi = 2.2^{+0.1}_{-0.1}$, and $\Gamma = 2.12^{+0.03}_{-0.02}$. The *XMM-Newton* spectrum was used to construct this model, since it provides better statistical constraints on very broad spectral features than the *Chandra* HEG spectrum. The ionized absorption model predicts a complex of narrow absorption lines between approximately 6.4 and 6.6 keV in the source frame that are inconsistent with the *Chandra* HEG spectrum, as shown in Figure 8. Narrow 1$s–2p$ iron absorption lines (from Fe xxvii at 6.4 keV up to Fe xxviii at 6.6 keV; Behar & Netzer 2002) are a generic feature of ionized absorption models in which there is significant iron L-shell absorption. We have confirmed that for $b = 0 \text{ km s}^{-1}$ a similarly strong absorption line complex is produced that would be readily visible in the HEG spectrum, and the strength of the absorption lines will increase with increasing $b$.

We conclude that a simple absorption model cannot account for the broad red wing of the iron line.

More complex absorption models are harder to constrain. It is possible that emission lines fill in the absorption lines, although this requires fine-tuning the ionization state and strength of emission so that no significant emission or absorption residuals are seen between $\sim 6.4$ and 6.5 keV, and we consider this scenario unlikely. A neutral partial covering model can be ruled out, because it is inconsistent with the *RXTE* spectrum above 10 keV (Reynolds et al. 2004). An ionized partial covering model (e.g., see Turner et al. 2005) cannot simply be ruled out, but if the partial covering component produces a strong absorption line.
similar to the simple absorption model discussed above, we can constrain the covering fraction to be \( f \leq 5\% \). For a larger covering fraction the absorption features should be visible in the HEG spectrum. It is difficult to introduce sufficient curvature to the continuum to significantly affect the red wing of the iron line, and we find that the inner radius of the Laor disk model is constrained to be \( r_{in} = 1.9 r_g \) with 99.9% confidence (for one interesting parameter), indicating that the broad red wing of the iron line is still present. If the Fe line comes from an accretion disk truncated at the innermost stable circular orbit, this indicates a black hole spin of \( a > 0.95 \). In this model the radial emissivity profile is \( r^{-q} \) with \( q = 3.4^{+0.1}_{-0.2} \), the disk inclination angle is \( i = 42^\circ \pm 1^\circ \), and the EW of the narrow Fe Kα emission line is 22 eV, consistent with the Chandra value.

The lower inclination angle of \( i = 26^\circ \) given in Table 1 results from attributing the drop in flux at 6.69 keV to the blue wing of the broad iron line rather than an absorption line. With the CCD resolution \( XMM-Newton \) data the \( i = 26^\circ \) interpretation wants an additional emission line at 6.9 keV (Fabian et al. 2002) to account for the flux above 6.7 keV. The value of \( i = 42^\circ \) in our model is consistent with, e.g., model 2 of Fabian et al. (2002). Furthermore, the \( i = 42^\circ \) model results in extra broad iron line flux up to \( \approx 6.9 \) keV and can account for the positive residuals around 6.8–6.9 keV seen, e.g., in Figure 4, which assumed an inclination of \( i = 26^\circ \).

### 3.3. The High-Ionization Absorber

The highly ionized gas giving rise to the H- and He-like absorption lines may be either intrinsic to the source or serendipitously located along the line of sight. In the former case, it must be outflowing from MCG–6-30-15 at \( v = 2.0^{+0.9}_{-0.5} \times 10^3 \) km s\(^{-1} \), whereas in the latter case it would have a velocity \( v = 0.3^{+0.3}_{-0.0} \times 10^3 \) km s\(^{-1} \) relative to the Galaxy.

The possibility that the absorbing gas is local is intriguing, since a number of other AGNs show iron absorption features that are kinematically consistent with a local origin (McKernan et al. 2004). In addition, O vii absorption is seen along every line of sight through the Galaxy for which we have a sufficiently high signal-to-noise ratio spectrum (Fang et al. 2003, 2005), although the O absorber need not be as highly ionized as the Fe absorber. If the H- and He-like Fe absorption seen in MCG–6-30-15 is simply due to an Fe absorption line overlaid (solid line) with the O absorber need not be as highly ionized as the Fe absorber. This complexity is well known, and while the overall ionization and velocity structure of warm absorbers is unknown, it is often modeled by a number of independent, discrete “zones” that can adequately reproduce the observed spectrum.
SPECTRAL STUDY OF Fe K BANDPASS IN MCG –6-30-15

We can estimate the mass outflow rate associated with the high-ionization component giving rise to the H- and He-like iron absorption lines using the ionization parameter, \( \log \xi = 3.6 \); ionizing luminosity, \( L_{\text{ion}} = 2 \times 10^{43} \text{ ergs s}^{-1} \) (assuming \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( q_0 = 0 \)); and outflow velocity, \( v = 2000 \text{ km s}^{-1} \). The ionization parameter \( \xi = L_{\text{ion}}/n r^2 \) implies \( n r^2 = 5 \times 10^{59} \text{ cm}^{-1} \). The mass outflow rate is then \( M_{\text{high}} = \Omega n r^2 v = 0.3(\Omega/4\pi) M_\odot \text{ yr}^{-1} \), giving a kinetic energy of \( L_{\text{KE}, \text{high}} = 4 \times 10^{41}(\Omega/4\pi) \text{ ergs s}^{-1} \), which is approximately 0.1\( L_X \). We note that these estimates depend on the unknown extent to which the absorbing material is clumped. Blustin et al. (2005) find that, for MCG –6-30-15, the warm absorber has an outflow rate of \( M_{\text{WA}} = 0.16 M_\odot \text{ yr}^{-1} \) and a kinetic luminosity of \( L_{\text{KE}, \text{WA}} = 10^{39} \text{ ergs s}^{-1} \). For a covering fraction of \((\Omega/4\pi) = 0.05\), the kinetic luminosity of the high-ionization component, \( L_{\text{KE}, \text{high}} = 2 \times 10^{40} \text{ ergs s}^{-1} \), dominates the energy budget of the outflow as a whole. The high-ionization component can also account for a significant fraction of the outflowing mass.

An estimate of the distance from the ionizing source can be obtained by using \( N \approx n \Delta r \), where \( \Delta r \) is the thickness of the absorber, and the ionization parameter \( \xi = L_{\text{ion}}/n r^2 \), to get \( r < 0.02(\Delta r/r) \text{ pc} \) for \( N = 10^{23} \text{ cm}^{-2} \) (§ 3.1) and \( \Delta r/r < 1 \). This is extremely close to the central engine and implies a density of \( n = 2 \times 10^6 \text{ cm}^{-3} \). The corresponding timescale for variability due to the motion of the absorber is \( r/v \approx 8(\Delta r/r) \text{ yr} \). We have examined the AO1 Chandra HETGS observation of MCG –6-30-15 (obs/433) and detect Fe xxv absorption at 6.7 keV with an EW of \( 167 (\pm 9) \text{ eV} \) and Fe xxvi absorption at 7.0 keV with an EW of \( -13^{+13} \text{ eV} \). (These can be seen in Fig. 5 of Lee et al. [2002b] and are consistent with the values listed in Table 2.) There is no evidence of variability in the EWs of the H- and He-like Fe lines between the AO1 observations of 2000 May 5 and August 21–22 and our more recent observations between 2004 May 19 and 27, although our measurement uncertainties do not provide strong constraints.

3.4. Conclusions

The Chandra HEG spectrum of the iron K bandpass of MCG –6-30-15 shows the following.

1. There are narrow absorption lines in the Chandra HEG spectrum from H- and He-like iron, requiring ion column densities of \( N_{\text{Fe xxv}} = (3 \times 10^{17}) - (3 \times 10^{18}) \text{ cm}^{-2} \) for \( b = 500-100 \text{ km s}^{-1} \), respectively, and \( N_{\text{Fe xxvi}} = (6 \times 10^{17}) - (4 \times 10^{18}) \text{ cm}^{-2} \) for \( b = 500-100 \text{ km s}^{-1} \), respectively. If the absorbing gas is photoionized with solar iron abundance and a velocity dispersion parameter of \( b = 100 \text{ km s}^{-1} \), we find \( \log N_{\text{HI}} = 23.2 \) and \( \log \xi = 3.6 \). The strongest two absorption lines predicted by the model between 2 and 6 keV are also detected, namely, S xi vi Ly\( \alpha \) and Si xiv Ly\( \alpha \).

2. The difference spectrum between the high- and low-flux states is well described by a power law in which a 6.7 keV absorption line is weakly detected, showing that the variable power-law emission also passes through the highly ionized absorber giving rise to the narrow H- and He-like absorption lines in the average spectrum.

3. Ionized absorption models, in which continuum curvature can mimic the broad red wing of the putative broad iron K line, predict iron K-shell absorption lines in the 6.4–6.6 keV range that are inconsistent with the Chandra HEG spectrum. In addition, the fact that the difference spectrum between the high- and low-flux states is well described by a power law strongly suggests that the curvature is not caused by absorption.

4. Applying the photoionization model used to described the H- and He-like absorption lines in the Chandra HEG spectrum to the XMM-Newton EPIC pn spectrum, we find that a broad iron line is still required. The Fe K\( \alpha \) emission extends down to \(< 1.9 r_g \), and if the line comes from an accretion disk truncated at the innermost stable circular orbit, this indicates a black hole spin of \( a > 0.95 \).}

5. The highly ionized absorber giving rise to the H- and He-like iron absorption lines in the Chandra HEG spectrum may be either intrinsic to the source or serendipitously located along the line of sight. In the former case it must be outflowing from MCG –6-30-15 at \( 2.0^{+0.4}_{-0.9} \times 10^3 \text{ km s}^{-1} \), whereas in the latter it would have a velocity \( 0.3^{+0.5}_{-0.3} \times 10^3 \text{ km s}^{-1} \) relative to the Galaxy. If the absorber is intrinsic to the source, it may be a highly ionized, high-velocity component of the warm absorber. This high-ionization component would dominate the energy budget of the outflow and account for a significant fraction of the outflowing mass.

Future observations of the iron K band with Astro-E2 will determine the velocity shift of the H- and He-like absorption lines with greater precision, help determine the location and nature of the highly ionized absorbing gas, and place stronger constraints on ionized partial-covering models. Such observations can also be used to search for multiple velocity components of absorption lines and to look for plasma diagnostics associated with the warm absorber.

We thank John Houck and Roderick Johnstone for their help with computer software, Simon Vaughan for the XMM-Newton spectrum, Barry McKernan and Sarah Gallagher for helpful discussions, and the anonymous referee for helpful comments and suggestions. Support for this work was provided by NASA through the Smithsonian Astrophysical Observatory (SAO) contract SV3-73016 to the Massachusetts Institute of Technology for support of the Chandra X-Ray Center, which is operated by the SAO for and on behalf of NASA under contract NAS 8-03060. J. C. L. thanks and acknowledges support from the Chandra fellowship grant PF2-30023; this is issued by the Chandra X-Ray Observatory Center, which is operated by SAO on behalf of NASA under contract NAS 8-39073.

REFERENCES

Behar, E., & Netzer, H. 2002, ApJ, 570, 165
Blustin, A. J., Page, M. J., Fuerst, S. V., Branduardi-Raymont, G., & Ashton, C. E. 2005, A&A, 431, 111
Cox, D. P., & Reynolds, R. J. 1987, ARA&A, 25, 303
Fabian, A. C., Iwasawa, K., Reynolds, C. S., & Young, A. J. 2000, PASP, 112, 1145
Fabian, A. C., Nandra, K., Reynolds, C. S., Brandt, W. N., Otani, C., Tanaka, Y., Inoue, K., & Iwasawa, K. 1995, MNARS, 277, L11
Fabian, A. C., & Rees, M. J., Stella, L., & White, N. E. 1989, MNARS, 238, 729
Fabian, A. C., & Vaughan, S. 2003, MNARS, 340, L28
Fabian, A. C., et al. 2002, MNARS, 335, L1

Fang, T., McKeel, C. F., Canizares, C. R., & Wolfire, M. 2005, ApJ, submitted
Fang, T., Sembach, K. R., & Canizares, C. R. 2003, ApJ, 586, L49
George, I. M., Turner, T. J., Netzer, H., Nandra, K., Mushotzky, R. F., & Yaqoob, T. 1998, ApJS, 114, 73
Gibson, R. R., Marshall, H. L., Canizares, C. R., & Lee, J. 2005, ApJ, 627, 83
Guainazzi, M., et al. 1999, A&A, 341, L27
Houck, J. C. 2002, in High-Resolution X-Ray Spectroscopy with XMM-Newton and Chandra, ed. G. Branduardi-Raymont (London: Mullard Space Science Laboratory), 17, http://www.mssl.ucl.ac.uk/ ~gbr/rgs_workshop/papers/houck _j.ps

House, L. L. 1969, ApJS, 18, 21
