CHANDRA HIGH-RESOLUTION X-RAY SPECTROSCOPY OF THE Fe K LINE IN THE SEYFERT 1 GALAXY NGC 3783

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ABSTRACT

We report on the results of detailed X-ray spectroscopy of the Fe K region in the Seyfert 1 galaxy NGC 3783 using the Chandra High Energy Grating Transmission Spectrometer (HETGS). There were five observations over an interval of ~125 days in 2001, each with an exposure time of ~170 ks. The combined data constitute the highest signal-to-noise Fe K spectrum having the best velocity resolution in the Fe K band to date (FWHM ~ 1860 km s⁻¹). The combined data show a resolved Fe Kα line core (FWHM = 1700⁺₁⁰₀⁻₂⁹₀ km s⁻¹) with a center energy of 6.397 ± 0.003 keV, consistent with an origin in neutral or lowly ionized Fe, located between the BLR and NLR, as found by Kaspi et al. in 2002. We also find that excess flux around the base of the Fe Kα line core can be modeled with either a Compton-scattering “shoulder” or an emission line (with about the same flux as the line core) from a relativistic accretion disk, having an inclination angle of 11° or less. This disk-line model is as good as a Compton-shoulder model for the base of the Fe Kα line core. In the latter model, we measured the column density to be 7.5⁺₂.₇₋₁.₆ × 10²³ cm⁻², which corresponds to a Thomson optical depth of ~0.60, so the line-emitting matter is not quite Compton-thick. An intrinsic width of 1500⁺₄₆₀⁻₄₄₀ km s⁻¹ FWHM is still required in this model. Moreover, more complicated scenarios involving both a Compton shoulder and a disk line cannot be ruled out. We confirm an absorption feature due to He-like Fe (FWHM = 6405⁺₉₂₀⁻₇₂₀₆ km s⁻¹) found in previous studies.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: individual (NGC 3783) — galaxies: Seyfert — line: profiles — X-rays: galaxies

1. INTRODUCTION

At least part of the Fe Kα fluorescent emission line in type 1 active galactic nuclei (AGNs) is believed to originate in a relativistic accretion disk around a black hole (e.g., see reviews by Fabian et al. 2000; Reynolds & Nowak 2003). The dominant peak energy of the Fe K line at ~6.4 keV appears to be ubiquitous, and this core of the line carries a substantial fraction of the total line flux (e.g., Nandra et al. 1997; Sulentic et al. 1998; Lubinski & Zdziarski 2001; Weaver et al. 2001; Yaqoob et al. 2002; Perola et al. 2002; Reeves 2003; Yaqoob & Padmanabhan 2004). It has been traditional to associate such narrow Fe Kα lines with an origin in distant matter, at least several thousand gravitational radii from the putative black hole (e.g., the optical broad-line region [BLR], the putative obscuring torus, or the optical narrow-line region [NLR]). However, Petrucci et al. (2002) recently reported a variable, narrow Fe K line in Mrk 841, supporting an accretion-disk origin (see also Longinotti et al. 2004). Moreover, variable, narrow Fe K line emission has been observed in the Seyfert 1 galaxy NGC 7314 (Yaqoob et al. 2003a). Thus, even narrow Fe Kα lines may have an important contribution from the accretion disk (Lee et al. 2002; Yaqoob et al. 2003a; Longinotti et al. 2004; Turner et al. 2004).

NGC 3783 is a fairly bright [F₂⁻¹₀ keV ~ (5–7.5) × 10⁻¹¹ ergs s⁻¹], moderate-luminosity [L₂⁻¹₀ keV ~ (1–1.5) × 10⁴³ ergs s⁻¹], nearly (z = 0.00973) Seyfert 1 galaxy that has been well studied in all wave bands. In the X-ray band, NGC 3783 was the target of the deepest observation with the Chandra High Energy Transmission Grating Spectrometer (HETGS; Markert et al. 1994) for any Seyfert galaxy, during a campaign in 2001, obtaining a net exposure time of ~830 ks. The spectra from this campaign represent the highest spectral resolution data with the best signal-to-noise ratio for any Seyfert galaxy available to date. The observing campaign was also designed to study variability and was broken up into five observations separated by various intervals ranging from days to months. The soft X-ray part of the HETGS data has been well studied by several research groups and has produced a wealth of new information and insights into the photoionized outflow and its variability (Kaspi et al. 2001, 2002; Netzer et al. 2003; Krongold et al. 2003). These results have been supplemented by studies using XMM-Newton (Behar et al. 2003; Reeves et al. 2004) and by studies in the UV band (e.g., Gabel et al. 2003a, 2003b). On the other hand, the high spectral resolution HETGS data for the Fe Kα line in NGC 3783 from the extended campaign in 2001 have not yet been fully exploited. Kaspi et al. (2002) reported measurements of the narrow core of the Fe Kα line and detection of a Compton-scattering “shoulder” on the red side of the core, indicating an origin for the line core in cold, optically thick matter, far from the nucleus (beyond the optical BLR). Results of variability studies of the Fe Kα line from within the extended observation campaign in 2001 have not yet been reported. A detailed study of the Fe Kα line from within the extended observation campaign in 2001 have not yet been reported. A detailed study of the Fe Kα line in NGC 3783 using XMM-Newton was presented by Reeves et al. (2004), who confirmed the Chandra measurements of the narrow core and, in addition, reported that a broad, relativistic disk line was not required by the data (a similar conclusion was reached by Kaspi et al. 2002 for the Chandra HETGS data). In this paper we specifically study the Fe Kα line in detail in NGC 3783 using the Chandra HETGS data from the extended campaign in 2001. We study the time-averaged spectrum, as well as the individual spectra from the five observations from the campaign in order to address line variability. We find that a Compton-shoulder model is not a unique description of the complexity in the Fe Kα line. A relativistic disk line model provides as good a
fit as the Compton-shoulder model. In §2 we describe the data and observations. In §3 we discuss the results of spectral fitting to derive parameters for the Fe Kα line core, from the time-averaged spectrum as well as from the separate observations. In §4 we confirm the detection of an Fe He-like absorption feature. In §§5 and 6 we describe the results of fitting a Compton-shoulder model and relativistic disk line model, respectively, to the excess flux at the base of the core of the Fe Kα line. Finally, we present our conclusions in §7.

2. OBSERVATIONS AND DATA

NGC 3783 was monitored over a period of ~125 days, starting 2001 February 24, with the Chandra HETGS during five snapshots. We refer to these snapshots as observations 1–5. HETGS consists of two grating assemblies, a high-energy grating (HEG) and a medium-energy grating (MEG), and it is the HEG that achieves the highest spectral resolution. The MEG has only half of the spectral resolution of the HEG and less effective area in the Fe K band, so our study focuses on the HEG data. The Chandra data were reduced and HEG spectra made exactly as described in Yaqoob et al. (2003b). We used only the first orders of the gratings, binned at 1024 s. The zero reference time in this composite light curve is UT 2001 February 24 19:06:15. The scale on the time axis is such that equal lengths correspond to equal time intervals.

Figure 1 shows the 2–7 keV light curves for the five observations, showing the count rates summed over the −1 and +1 orders of both the MEG and the HEG, binned at 1024 s. It can be seen that the observations, each of duration ~2 days, were designed to probe timescales of ~1 day and less, ~1, 2, 3, and 4 weeks, and 3 and 4 months. The 2–7 keV continuum variability over the first ~2 weeks of the campaign was confined to the flux remaining within about ±25% of the mean during that period, but in observation 4, about a month into the campaign, the overall flux was higher than the mean in the first two weeks of the campaign by ~50% (see Fig. 1). However, the variability about the new mean flux during observation 4 was still about ±30% relative to the mean in observation 4. In the final observation the 2–7 keV flux began back at its level at the beginning of the campaign, but by the end of the ~2 day observation it had risen by ~50%, compared to the level at the beginning of final observation of the campaign. The excess variance above the expectation for Poisson noise (e.g., Turner et al. 1999), calculated over the entire ~4 month monitoring period from the light curve in Figure 1, is (4.52 ± 0.28) × 10−2.

3. SPECTRAL FITTING RESULTS

We used XSPEC version 11.2 (Arnaud 1996) for spectral fitting. Since we were interested in utilizing the highest possible spectral resolution available, we used spectra binned at 0.0025 Å, and this amply oversamples the HEG resolution (0.012 Å FWHM). The C-statistic was used for minimization. By definition, calculation of the C-statistic requires only knowledge of the number of counts in a bin, but for spectral plots, the error bars correspond to asymmetric errors calculated using the approximations of Gehrels (1986). All model parameters will be referred to the source frame, unless otherwise noted. Note that since all models were fitted by first folding through the instrument response before comparing with the data, the derived model parameters do not need to be corrected for instrumental response.

3.1. Simple Continuum Model

Our method is first to fit a simple empirical model to the continuum and extract parameters for the core of the Fe Kα emission line to establish whether there is any interobservation variability of the line parameters. Since we are comparing line parameters and the line core is narrow (see Yaqoob & Padmanabhan 2004), this is good enough to guide subsequent, more detailed analysis. Accordingly, we then describe more physical (and more complex) models for the continuum and absorption and show the extent of the sensitivity of the absolute parameters of the Fe Kα emission line core to details of these models.

Thus, we fitted a simple power law plus Gaussian emission line model over the 2–7 keV band for each of the five spectra.

5 See http://space.mit.edu/CXC/calib/hetgcal.html.
TABLE 1
CORE Fe K Line Chandra HEG Spectral Fitting Results

| Observation | E (keV) | I (10⁻⁵ photons cm⁻² s⁻¹) | EW (eV) | FWHM (km s⁻¹) | F (10⁻¹¹ ergs cm⁻² s⁻¹) | L (10⁶ ergs s⁻¹) |
|-------------|--------|---------------------------|---------|---------------|--------------------------|-----------------|
| 1           | 6.401±0.008 (6.390–6.412) | 4.77±1.31 (3.22–6.58) | 75±21 (51–103) | 2320±125 (990–4055) | 5.0 | 1.1 |
| 2           | 6.393±0.005 (6.380–6.403) | 5.42±2.19 (3.82–7.33) | 85±27 (60–115) | 2545±160 (1365–4415) | 5.1 | 1.1 |
| 3           | 6.394±0.005 (6.387–6.401) | 5.19±0.98 (3.77–6.83) | 81±17 (59–107) | 1205±70 (0–2540) | 5.2 | 1.1 |
| 4           | 6.396±0.005 (6.389–6.402) | 5.61±1.15 (4.08–7.31) | 66±15 (48–86) | 1255±70 (0–2305) | 7.4 | 1.6 |
| 5           | 6.401±0.005 (6.392–6.411) | 3.86±0.33 (2.52–5.39) | 51±13 (33–71) | 1345±80 (0–2715) | 6.1 | 1.3 |
| Total       | 6.397±0.005 (6.393–6.401) | 4.90±0.55 (4.21–5.64) | 70±9 (60–80) | 1700±110 (1180–2250) | 5.8 | 1.2 |

Notes.—Chandra HEG data, fitted with a power law plus Gaussian Fe Kα emission line model in the 2–7 keV band (see § 3). The purpose of these fits is primarily a comparison of the Fe Kα emission line parameters (see Figs. 3, 4, and 6). Absolute values of the line intensity are model-dependent, but the peak energy and width of the Fe Kα line core are insensitive to the continuum and absorption model. The last row gives measurements from the summed spectrum (with ~830 keV exposure time), as derived in Yaqoob & Padmanabhan (2004). All fit parameters are quoted in the source rest frame. Line widths are intrinsic, since they have already been corrected for the instrumental line response function. Statistical errors are for three interesting parameters and correspond to the 68% confidence level.

We report the results of investigating this apparent variability of the width of the Fe Kα line core further in § 3.3, but first we report the results of investigating the dependence of the Fe Kα core line parameters on the details of modeling the continuum and absorption.

3.2. Dependence of Fe Kα Line Parameters on Continuum and Absorption Modeling

Here we use the ~830 ks MEG and HEG spectra (i.e., summed over the five observations) to investigate in detail the effect of using an oversimplified empirical continuum (as described above) on the derived Fe Kα core line parameters. It is well known that there is a complex photoionized absorber in NGC 3783, with at least two components. The absorber has been modeled in great detail by several research groups, using Chandra and XMM-Newton data (e.g., Kaspi et al. 2002; Netzer et al. 2003; Krongold et al. 2003; Behar et al. 2003). Since highly ionized components of the absorber can affect the data even in the Fe K band, it is conceivable that the warm absorber can affect interpretation of the broad part of the Fe Kα emission line. In fact, the apparent lack of a broad Fe Kα emission line in recent XMM-Newton data was attributed by Reeves et al. (2004) to the complex absorber not being modeled adequately in previous analyses. Reeves et al. (2004) also reported an absorption line due to He-like or H-like Fe in the same XMM-Newton data. We expect the effect of the photoionized absorber on the narrow Fe Kα emission line core to be unimportant, but since we are also searching for spectral variability over a broader energy range than just the line core and revisiting the question of the presence of a broad Fe Kα line, we constructed a model of the photoionized absorber.

We compiled a spectral energy distribution (SED) from the literature to use as an input to the photoionization code XSTAR, which was then used to construct grids of models for spectral fitting. Full details and results for the complex absorber modeling are given in McKernan et al. (2005). For the present purpose of Fe Kα line modeling, we did not attempt to model the individual soft X-ray absorption lines and features at the level of detail accomplished in the dedicated studies mentioned above. We found that a two-component absorber combined with a broken power-law continuum was sufficient to model the broadband MEG and HEG data. The model was derived by first fitting the spectrum...
corresponding to the energies of the Fe K absorption feature found in the xxi emission line. The arrow in (a) indicates the position in energy of the Fe K absorption feature found in the XMM-Newton data by Reeves et al. (2004).

MEG 0.5–7 keV data, using an additional Gaussian to model the Fe Kα emission line core, whose parameters were initially frozen at the values derived using the simple power-law continuum model (§3.1). Then this model was fitted to the 0.8–9 keV HEG data with all parameters except the hard X-ray slope frozen. Then, restricting the energy range to 2–7 keV (in order to directly compare derived emission-line parameters with the empirical continuum fits in §3.1), the Gaussian emission line parameters (peak energy, width, and intensity) were allowed to float and the best fit found. The photoionized absorber components had column densities of $4.7 \times 10^{21}$ and $3.5 \times 10^{22}$ cm$^{-2}$, with corresponding ionization parameters $\log \xi = 0.74$ and 2.21, respectively (where $\xi \equiv L_{\text{ion}}/n_{e}r^{2}$, $L_{\text{ion}}$ being the $1–1000$ ryd ionizing luminosity, $n_{e}$ the electron density, and $r$ the source to absorber distance). The soft X-ray modeling is discussed in detail in McKernan et al. (2005), as well as in the several studies mentioned above, so we do not discuss it any further. Figure 2a shows the ratio of the summed HEG data to this model in the 2–7 keV band, with the data binned at 0.005 A. Figures 2b–2f show the ratio of the data, from each of the five snapshots, to this same model, with only the overall normalization adjusted to obtain the best-fit. Aside from linelike features between ~6 and 7 keV, the model gives a strikingly good fit to the spectra from all five of the separate observation data sets. We address the possible origin of these residuals in more detail in §6. The apparently variable linelike features at ~7 keV are likely due to Fe xxvi Lyα emission (which, blended with Fe Kβ, was detected in XMM-Newton data by Reeves et al. 2004; see also Kaspi et al. 2002).

Figure 3 shows joint, two-parameter, 99% confidence contours for the Fe Kα emission line core from the ~830 ks, Chandra HEG spectrum of NGC 3783, illustrating the effects of different levels of approximation in modeling the continuum. Black contours correspond to a simple power-law continuum (fitted in the 2–7 keV band), red contours correspond to a model including a photoionized absorber, as described in §3.2, and blue contours include a Compton-reflection continuum in addition to the photoionized absorber, also described in §3.2. The emission line is modeled by a simple Gaussian, and (a) shows the line intensity vs. center energy, while (b) shows the line EW vs. FWHM. All quantities are in the rest frame of NGC 3783. It can be seen that the center energy of the line is not sensitive to details of modeling the continuum, but there is some model dependency on the line intensity, EW, and FWHM. However, the differences are not statistically significant at the 99% confidence level. The dotted line in (a) corresponds to the rest energy of Fe Kα (6.400 keV), and the dotted line in (b) corresponds to the HEG FWHM resolution at the observed center energy of the Fe Kα line.
simple and complex continuum models. Black contours show the results using the simple, empirical power-law continuum, and red contours show the results using the warm absorber plus complex intrinsic continuum described above. Specifically, Figure 3a shows the Fe K line intensity versus line-center energy contours, while Figure 3b shows the EW versus FWHM contours. It can be seen that although both the line intensity and EW are consistent at the 99% confidence level from the two different continua, the fits using a complex continuum give values for the best-fitting line intensity and EW that are \( \sim 20\% \) higher than those obtained using the simple power-law continuum only. This is because the intrinsic flux from the line has to be larger to compensate for the absorption in the complex model. However, we do not in fact know whether the warm absorber lies farther from the X-ray continuum source than the Fe K line emitter, so there is an inherent uncertainty in the Fe K line intrinsic intensity that will only be resolved when we are able to constrain the geometry of the system better with future missions (but see §§ 5 and 6).

The Chandra HEG data are not sensitive enough to strongly constrain a Compton-reflection continuum. However, we investigated the effect of including a Compton-reflection continuum (in addition to the complex ionized absorber model described above), since it is conceivable that it could still affect the derived line parameters as it has a complex shape in the 6–7 keV region due to the Fe K edge. Moreover, if the Fe K\( \alpha \) emission line is formed in optically thick matter (for example, reflection from the inner surface of a putative obscuring torus), a Compton-reflection continuum is expected. We used the pexrav model in XSPEC (see Magdziarz & Zdziarski 1995). Although this model is based on a disk geometry, it is adequate for our purpose since the Chandra data are not sensitive to the differences in geometry.

Again, since the data cannot constrain this model well, the parameters of the reflection model were fixed at nominal values (except for the photon index and normalization of the intrinsic power-law continuum). Specifically, we fixed the Fe abundance at the default solar value, the disk inclination angle at 30\( ^\circ \), and the effective solid angle of the reflector at 2\( \pi \) (i.e., the “reflection factor,” \( R = 1 \)). However, in §§ 5 and 6 we investigate the effect of allowing \( R \) to be free. The \( \varepsilon \)-folding cutoff energy of the power law was fixed at 300 keV, well outside the range of the data.

Figure 3a shows the joint, two-parameter, 99% confidence contour (blue) of the Fe K\( \alpha \) line intensity versus line-center energy, and Figure 3b shows the two-parameter, 99% confidence contour of the line EW versus FWHM. These contours are directly compared with the corresponding contours derived with the Compton-reflection continuum omitted (red), and with only a simple power law (black). It can be seen that the effect of omitting the Compton-reflection continuum on the derived parameters of the core of the Fe K\( \alpha \) emission line is negligible, even at the 99% confidence level. The effect of the ionized absorber on the line parameters is far more important.

### 3.3. Variability of the Fe K\( \alpha \) Line Core

Figure 4a shows the joint, two-parameter, 99% confidence contours of the Fe K\( \alpha \) line intensity and EW versus center energy. Remaining contours were obtained from the individual snapshots as follows: large black contour (observation 1); red contour (observation 2); green contour (observation 3); blue contour (observation 4); magenta contour (observation 5). See § 3 for details. It can be seen that there is no discernible variability at the 99% confidence level. The dotted line is at 6.400 keV in the rest frame of NGC 3783. (b) Joint, two-parameter confidence contours of line EW vs. center energy (both in the AGN rest frame) for the Fe K\( \alpha \) emission line core (modeled with a simple Gaussian) from Chandra HEG spectra of NGC 3783. The continuum was modeled by a simple power law, fitted over the 2–7 keV energy range. The small, black contour was obtained from the total, \( \sim 830 \) ks HEG spectrum. Remaining contours were obtained from the individual snapshots as follows: large black contour (observation 1); red contour (observation 2); green contour (observation 3); blue contour (observation 4); magenta contour (observation 5). See § 3 for details. It can be seen that there is no discernible variability at the 99% confidence level. The dotted line is at 6.400 keV in the rest frame of NGC 3783. (b) Joint, two-parameter confidence contours of line EW versus center energy (both in the AGN rest frame) for the Fe K\( \alpha \) emission line core in the NGC 3783 HEG data, using the same model as in (a). Black contour shows the 99% confidence region for the total, \( \sim 830 \) ks HEG spectrum. Remaining contours were obtained by combining the snapshots from observations 1 and 2 (blue contour) and observations 3, 4, and 5 (red contour). Dotted lines show the 68% and 90% confidence regions, and solid lines show the 99% confidence contours. These combinations were formed after examining the contours of all five observations separately and grouping them according to similar widths. It can be seen that there is marginal evidence for a change in the effective width of the line, which appears to be resolved in observations 3, 4, and 5 but not in observations 1 and 2 (the dotted line corresponds to the HEG FWHM resolution at the observed center energy of the line).
present Chandra observations, shows that the continuum varies significantly on all timescales in this range (Markowitz & Edelson 2004). Therefore, all we can say is that the actual response time of the Fe Kα line core must be greater than ~2 days because if the continuum varies more rapidly than the response time, the Fe Kα line core intensity measured will correspond to some average continuum level. If we take t > 169 ks as the response time for the Fe Kα line core–to–continuum variations, we get r > 5 × 10^{15} cm for the location of the line emitter relative to the continuum source (the recombination timescale likely does not play a role here since the center energy of the Fe Kα line core indicates neutral Fe). For a central black hole mass of 2.9 × 10^{8} M_s (Peterson et al. 2004), this corresponds to r > 1000 r_g, where r_g ≡ GM/c^2 is the gravitational radius. However, the FWHM of the Fe Kα line core (~1700 km s^{-1} from the total combined spectrum) places its origin much farther from the central black hole. The actual width already indicates that it might coincide with the outer BLR/inner NLR. Note that in the present paper, all quoted line widths derived from spectral fitting are already corrected for the instrumental line-spread function.

Assuming a virial relation and an rms velocity dispersion of √(3rFWHM^{2} / 2) (e.g., Netzer 1990) places the line emitter at 0.06 pc, or ~70 lt-days from the central continuum source (using the above mass). If some of the line width is not kinematic in origin (e.g., if there are multiple lines from different ionization states of Fe), then this distance is even greater. This is consistent with the lack of response of the line intensity to continuum variability. However, the lack of variability of the narrow Fe Kα line core is not necessarily an expected result, because variability in the narrow Fe Kα line core has been observed in Mrk 841 (Petrucci et al. 2002), independent of the continuum (and that result is still not fully understood; but see Longinotti et al. 2004).

In § 3.1 (Table 1) we showed that observations 1 and 2 appeared to have a somewhat broader Fe Kα line core than observations 3–5. To investigate further, we combined the five HEG spectra into two groups, one spectrum from observations 1 and 2 and the other spectrum from observations 3–5. Figure 4b shows the joint, two-parameter, 68%, 90%, and 99% confidence contours of the Fe Kα line EW versus the FWHM for these two grouped spectra, compared with the 99% contour obtained from the mean, time-averaged spectrum. Indeed, the 68% confidence contours from observations 1 and 2 do not overlap with those from observations 3–5, the latter showing a narrower line width than the former, with the narrower line having a somewhat smaller flux than the broader line. Thus, at 68% confidence the Fe Kα line core appears to be broader and more intense in observations 1 and 2 than in observations 3–5. However, the 90% and 99% confidence contours do overlap, so we cannot say that the line width varied at 90% confidence or greater. On the other hand, the line is resolved by the HEG at higher than 99% confidence in observations 1 and 2 but is not resolved at 99% confidence in observations 3–5. Future instrumentation will have to address the question of variability in the line width.

4. He-LIKE Fe ABSORPTION FEATURE

Kaspi et al. (2002) reported He-like Fe absorption in the Chandra HETGS data. Reeves et al. (2004) detected the absorption line from an XMM-Newton observation of NGC 3783 (in 2001 December), centered at 6.67 ± 0.04 keV (in the source rest frame) with an EW of 17 ± 5 eV. The line was attributed to Fe xxv l^2s^-1ls^2p resonance absorption, and it was not resolved by the CCDs. Evidence of this absorption feature can be seen in Figure 2 (an apparent absorption dip is indicated by an arrow). We modeled the feature by adding an inverted Gaussian to the two-component warm absorber plus broken power law model described in § 3 (including the Gaussian emission line). All parameters except for the hard power-law slope, the overall continuum normalization, and the three absorption-line parameters (center energy, intrinsic width, and line intensity) were frozen at their best-fitting values. The C-statistic decreased by 9.2 upon the addition of the absorption line, which corresponds to a detection significance of only 99% for three additional free parameters. For the line-center energy, EW, and intrinsic width, we measured 6.62_{-0.06}^{+0.07} keV, 12_{-5}^{+8} eV, and 6405_{-2670}^{+5020} km s^{-1} FWHM, respectively (errors are one-parameter, 90% confidence, to facilitate direct comparison with the XMM-Newton results of Reeves et al. 2004). Thus, the Chandra HETGS and XMM-Newton measurements are consistent with each other.

5. Fe Kα LINE COMPTON SHOULDER

Using the same NGC 3783 Chandra HEG data as described in the present paper, Kaspi et al. (2002) noted the detection of a so-called Compton shoulder on the red side of the peak of the Fe Kα emission line. This structure is due to the core Fe Kα emission line photons Compton-scattering on electrons in the medium in which the line is formed, before escaping the medium and reaching the observer. If the material in which the line is formed is not too hot (i.e., kT ≪ 6.4 keV), the Compton scattering results in the line photons losing energy so that the scattered emission appears redward of the peak of the line. The relative magnitude of the Compton shoulder relative to the peak line flux increases with optical depth of the medium, until the medium becomes optically thick (see, for example, Matt 2002 for a theoretical description and Monte Carlo calculations). The peak of the once-scattered photon energy distribution is expected at two Compton wavelengths longer than the wavelength of the unscattered line photons. For a line at 6.4 keV, this is ~6.25 keV in the rest frame of NGC 3783, or 6.19 keV in the observed frame. The excess flux to the red side of the Fe Kα line core can be seen in Figures 2a and 5 and does in fact appear to extend down to the appropriate energy.
We applied a model of the Compton shoulder to the NGC 3783 HE data. For the line scattering we used the XSPEC model of Watanabe et al. (2003). The intrinsic width of the emission line in this model is much less than the instrument resolution and includes no kinematic information, and so is rather unphysical. During preliminary fitting we found that the model always left excess flux blueward of the Fe Kα line core. Therefore we convolved the line profile with a Gaussian whose width was a free parameter, in order to mimic Doppler broadening of the intrinsic line profile. We used the broken power law plus two-component warm absorber, with a Compton-reflection continuum as the baseline model, as described in §3.2. The parameters of the warm-absorber and Compton-reflection models were fixed at the values described in §3.2. The fitting was performed between 2–9 keV.
(i.e., the high-energy end of the fitted range was now extended from 7 up to 9 keV). Only the hard X-ray slope, the overall continuum normalization, and the column density of the Compton-scattering medium were free parameters. Since the Fe Kα line peak energy indicates low ionization states of Fe and is consistent with Fe i, the temperature of the scattering medium must be low and we assumed that the medium is neutral ("cold"). The data, best-fitting model, and data/model ratio are shown in Figure 6a. Note that the He-like Fe absorption line discussed in § 4 has deliberately not been modeled in Figure 6a in order to clearly show its presence and magnitude, especially in the data/model ratios, and to facilitate comparison with the XMM-Newton data. We obtained a FWHM of 1500\(+140\)\,-\,\(140\) km s\(^{-1}\) for the width of the Gaussian used to convolve the Compton-scattered line profile. The column density that we derived was \(7.5^{+2.7}_{-0.7} \times 10^{23} \) cm\(^{-2}\) (90\%, one-parameter errors). This corresponds to a Thomson depth of \(\sim 0.60\), which is not quite Compton-thick. The Thomson depth of the scattering medium must be less than \(\sim \sqrt{2}\), or else the mean number of scatterings would be \(\sim 2\) and the peak energy of the scattered photons would be much lower than measured (the scattered line photons would have a distribution with significant flux down to four Compton wavelengths below the zeroth-order line peak). A Thomson depth of \(\sqrt{2}\) corresponds to \(\sim 1.7 \times 10^{24} \) cm\(^{-2}\).

Ideally, we would self-consistently model the Compton-reflection continuum and the Compton-scattered line since both are produced by the same physical process. When we allowed the relative normalization of the Compton-reflection continuum, \(R\), to be a free parameter, we obtained \(R = 1.0^{+0.3}_{-0.2}\) (justifying \(R = 1\) in the fits thus far). However, the Compton-reflection continuum model is calculated for an optically thick disk, but the emission line may be produced in transmission since we measured a small Thomson depth from the Compton shoulder. Better data are required to justify more sophisticated modeling.

6. RELATIVISTIC DISK LINE MODEL

We investigated whether a relativistically broadened Fe Kα line (in addition to a narrow Gaussian component) could also account for the Fe Kα line profile in NGC 3783. We fitted the 2–9 keV HEG data using a broken power law plus two-component warm absorber, with a Compton-reflection continuum as the baseline model, as described in § 3.2. Initially, the Compton-reflection parameter \(R\) was fixed at unity, which corresponds to the expected steady state normalization of the reflected continuum from a neutral ("cold") Compton-thick disk subverting a solid angle of \(2\pi\) at the X-ray source. Preliminary spectral fitting with \(R\) free showed that the best-fitting value is \(R \sim 1\) in any case (as in § 5), and we give statistical errors when \(R\) was a free parameter below. In addition to the above model components, we included a Gaussian (to model the line core) and an emission line from a relativistic disk around a Schwarzschild black hole (e.g., see Fabian et al. 1989). The energy, intrinsic width, and intensity of the Gaussian were free parameters. The inner radius of line emission from the disk was initially fixed at \(6r_g\) (\(r_g \equiv GM/c^2\)), and the outer radius was fixed at 1000\(r_g\). The line radial emissivity was assumed to be a power law (line emissivity proportional to \(r^{-\gamma}\)), with the index \(\gamma\) free. In the disk rest frame the emission-line energy was fixed at 6.4 keV. The disk inclination angle and overall line intensity were also free parameters. Thus, there were a total of seven free parameters for this model, including the continuum slope and normalization.

The data, best-fitting model, and data/model ratio are shown in Figure 6b. It can be seen that the fit is as good as that for the Compton-scattering model, shown in Figure 6a. Again, we deliberately did not model the He-like Fe absorption feature discussed in § 4 in order to clearly show its effect and to facilitate comparisons between Chandra and XMM-Newton data. In the 5.7–6.9 keV energy band shown in the figure, the \(C\)-statistic for the disk-line model is less than that for the Compton-shoulder model (§ 5) by only 1.6 for an additional three free parameters. Thus, although the disk-line model is not statistically preferred over the Compton-shoulder model, it cannot be ruled out. The center energy of the Gaussian was 6.399 keV, with statistical errors similar to those obtained from simpler continuum models (Table 1). Since the peak energy was well-determined, this parameter was fixed when deriving the statistical errors for the other parameters in the model (in this section, all errors are 90\% confidence, one-parameter, or \(\Delta C = 2.706\)). The Gaussian line FWHM obtained was \(1460^{+470}_{-580} \) km s\(^{-1}\). The Gaussian line width was then fixed at the best-fitting value in order to derive statistical errors on the remaining model parameters, in order to avoid the spectral fitting becoming unstable.

We obtained EWs of \(56^{+14}_{-10}\) and \(39^{+16}_{-16}\) eV for the Gaussian and disk emission line components, respectively (all line measurements are in the source frame). The radial emissivity index measured for the disk-line emission was \(\gamma = 1.90^{+0.63}_{-0.57}\). We recall that \(\gamma = 1\) corresponds to the case of time-steady illumination of a thick disk subtending a \(2\pi\) solid angle at the X-ray source. We note that De Rosa et al. (2002) obtained \(R = 0.71^{+0.29}_{-0.30}\) from noncontemporaneous BeppoSAX data for NGC 3783, and Markowitz et al. (2003) obtained \(R = 0.62 \pm 0.12\) from RXTE data that overlapped with the first three Chandra observations reported in the present paper, consistent within the errors with the Chandra value. However, Markowitz et al. (2003) also reported \(R = 0.47^{+0.05}_{-0.04}\) for RXTE data taken over a \(\sim 3.2\) yr period between 1999 and 2002. Over such a long timescale, variability can obviously be a factor responsible for the smaller value of \(R\).

Upon allowing the outer disk radius to be a free parameter in the original disk model, with \(R\) fixed at 1.0, we obtained a lower limit on its value of \(\sim 540r_g\). The inner disk radius and \(q\) are correlated in the sense that they affect the overall width of the emission line: larger inner radii allow steeper radial emissivity index \(q\) since the part of the disk giving the broadest part of the line with a steep \(q\) would then be missing. The data do not allow the ambiguity between \(q\) and the inner radius to be removed. By examining confidence contours of \(q\) versus \(r_{in}\) we found that a radial emissivity steeper than even \(r^{-3}\) is allowed if \(r_{in}\) is of the order of 100\(r_g\) or larger.

We note that our results for the relativistic disk line are not inconsistent with the findings of Reeves et al. (2004), namely, that the XMM-Newton data do not require a disk line when the warm absorber is taken into account. Reeves et al. (2004) obtained a 90\% upper limit on the EW of a disk line of 35 eV. However, this assumed a steep emissivity index (\(q = 3\)) combined with a small inner disk radius (\(r_{in} = 6r_g\)), and a disk inclination angle of 30°. With a flatter emissivity and a smaller inclination angle, as obtained from the Chandra HEG data, a larger EW is allowed because the disk line width is narrower. Thus, the Chandra HEG and XMM-Newton measurements are consistent with each other. The reason why the XMM-Newton data do not yield a significant detection of the disk line is that the Chandra HEG data are more sensitive to a narrow disk line, due to the factor of \(\sim 4\) better spectral resolution. In Figures 6c and 6d we show that both the best-fitting Chandra HEG Compton-shoulder model and
disk-line model, respectively, fit the XMM-Newton data equally well. For fitting the XMM-Newton data (the same data as in Reeves et al. 2004, which were taken at a different time from the Chandra data), all parameters except the overall normalization and the power-law slope were fixed at their Chandra best-fitting values. Again, the He-like Fe absorption feature discussed in §4 was deliberately not modeled here in order to facilitate comparison between the Chandra and XMM-Newton data.

Although Fe Kβ line emission is expected to accompany Fe Kα line emission, the HEG data are not so sensitive to Fe Kβ lines because the branching ratio is 17:150 for Kβ:Kα. Having said that, linelike residuals are apparent in the spectral ratios shown in Figure 2, but some part of this line emission could be due to Fe xxvi Lyα. Reeves et al. (2004) reported significant line emission at ~7 keV from XMM-Newton data and obtained an EW of 20 ± 5 eV for Fe xxvi Lyα after accounting for Fe Kβ emission. Since Fe Kβ line emission is expected to accompany the Fe Kα line emission, we self-consistently added Gaussian and disk-line Fe Kβ emission with the expected branching ratio to the Gaussian plus disk line model described above in order to test the Chandra HEG data for Fe xxvi Lyα emission. We modeled the latter with an additional Gaussian, fixing the energy at 6.966 keV (e.g., see Pike et al. 1996) but leaving the intrinsic width free for the summed, ~830 keV HEG spectrum, but fixing it at the resulting best-fit value for the individual spectra from observations 1–5. The best-fitting intrinsic width from the summed HEG spectrum was 9200 km s⁻¹ FWHM. However, we did not obtain a very significant detection (ΔC was always less than 2.7) for either the summed spectrum (90%, one-parameter upper limit: 17 eV) or the individual spectra from the five observations. Although Figure 2 shows evidence of variability of the linelike residuals at ~7 keV, we could only obtain upper limits on the EW (29, 27, 65, 41, and 14 eV for observations 1, 2, 3, 4 and 5, respectively). All of the values of the Fe xxvi Lyα EW upper limits that we obtained are consistent with the EW measurements from XMM-Newton data by Reeves et al. (2004).

7. CONCLUSIONS

We have presented results of X-ray spectroscopy of the Fe K line region in NGC 3783 from an extended monitoring campaign with the Chandra High Energy Grating Transmission Spectrometer (HETGS). Consistent with previous studies, the Fe Kα line core is resolved in the time-averaged spectrum by the high-energy grating (HEG) and has a center energy indicating an origin in neutral or lowly ionized Fe. Despite a factor of ~1.5 variation in the X-ray continuum luminosity, we measured no variability in the intensity of the Fe Kα line core during five observations comprising the observing campaign, over ~125 days. The lack of response to the continuum is consistent with the fact that a virial interpretation of the line FWHM (~1700 km s⁻¹) gives a distance between the putative central black hole and the line emitter of at least 0.06 pc, or 70 lt-days. However, we detected marginal evidence of variability in the intrinsic width of the Fe Kα line core. In two out of the five snapshots, the Fe Kα line was resolved and had a FWHM of ~2300 km s⁻¹, while in the other three snapshots the line was unresolved. This apparent variability was not related to the X-ray continuum level. At 68% confidence, the Fe Kα line core was broader and had a higher flux in the first two ~170 ks snapshots than in the last three. If the line width variability is real, it could be due to changes in the matter distribution and/or ionization state as a function of distance from the central engine and would be important to investigate with future missions.

We found that the excess flux around the base of the Fe Kα line core can be modeled by an emission line from a relativistic disk rotating around a black hole, as well as a model in which line core photons are Compton-scattered (forming a “Compton shoulder” on the red side of the line peak). More realistic modeling should self-consistently include Compton scattering of line photons, whether the line photons originate in an optically thick disk or more distant matter. Also, the Compton-scattered continuum should be self-consistently computed. In principle, measurement of the unscattered and scattered line photons, along with the reflected continuum, would constrain whether the core of the Fe Kα line originates in optically thick matter (such as the putative obscuring torus) or in optically thin matter (e.g., the BLR and/or NLR). However, the signal-to-noise ratio of the current data is not sufficient to distinguish between these scenarios. We note that a Compton shoulder has not been detected in any other Chandra HETGS observation of a Seyfert 1 galaxy (Yaqoob & Padmanabhan 2004). If this is verified by higher signal-to-noise data, it would suggest that the Fe Kα line core is in general likely to originate in optically thin matter. In the case of NGC 3783, the EW of the Fe Kα line core deduced from the composite Gaussian plus disk line model can easily be produced by optically thin matter with N_H ~ 10²³ cm⁻², covering less than half the sky (e.g., see Yaqoob et al. 2001).

Modeled with a relativistic disk line, the disk inclination angle was constrained to be less than 11° and the emission-line flux from the disk is comparable to that in the Fe Kα line core. The line-modeling included a continuum with a complex photoionized absorber and Compton reflection modifying the intrinsic continuum. We showed that the Chandra HEG data are consistent with the XMM-Newton data in the sense that the same disk-line model can account for both data sets, even with these continuum complexities. Of course, with the current data it is not possible to rule out more complicated scenarios involving, for example, a disk line modified by Compton scattering, as mentioned above. We also confirmed detection of an absorption feature in the Fe K band (at 6.67 ± 0.04 keV, and with an EW of 17 ± 5 eV), likely due to He-like Fe absorption. On the other hand, evidence for Fe xxvi Lyα emission was marginal in the HEG data.

Future observations with higher spectral resolution, as afforded by Astro-E2, will be able to resolve important ambiguities remaining in the Fe K band in NGC 3783. In particular, it will be possible to determine whether the Fe Kα line core is composed of more than one line component and to determine whether the broad part of the Fe Kα line is really due to a relativistic disk.

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