THE CORES OF THE Fe K LINES IN SEYFERT 1 GALAXIES OBSERVED BY THE CHANDRA HIGH ENERGY GRATING

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ABSTRACT

We report on the results of 18 observations of the core, or peak, of the Fe Kα emission line at ~6.4 keV in 15 Seyfert 1 galaxies using the Chandra High Energy Grating (HEG). These data afford the highest precision measurements of the peak energy of the Fe Kα line and the highest spectral resolution measurements of the width of the core of the line to date. We were able to measure the peak energy in 17 data sets, and, excluding a very deep observation of NGC 3783, we obtained a weighted mean of 6.404 ± 0.005 keV. In all 15 sources the two-parameter, 99% confidence errors on the line peak energy do not exclude fluorescent Kα line emission from Fe I, although two sources (Mrk 509 and 3C 120) stand out as very likely being dominated by Kα emission from Fe XVII or so. We were able to measure the line core width in 14 data sets and obtained a weighted mean of 2380 ± 760 km s⁻¹ FWHM (excluding the NGC 3783 deep exposure), a little larger than the instrument resolution (~1860 km s⁻¹ FWHM). However, there is evidence of underlying broad-line emission in at least four sources. In fact, the width of the peak varies widely from source to source and may in general have a contribution from the outer parts of an accretion disk and more distant matter. For the disk contribution to also peak at 6.4 keV requires greater line emissivity at hundreds of gravitational radii than has been deduced from previous studies of the Fe Kα line.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: Seyfert — line: profiles — X-rays: galaxies

1. INTRODUCTION

At least part of the Fe Kα fluorescent emission line in type I 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 Kα 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. 1997a; Sulentic et al. 1998; Lubinski & Zdziarski 2001; Weaver, Gelbord, & Yaqoob 2001; Yaqoob et al. 2002; Perola et al. 2002; Reeves 2002). Often, the broad part of the Fe Kα line is absent, leaving only the narrow core. 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 Kα line in Mrk 841, supporting an accretion disk origin. Moreover, rapidly 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 a significant contribution from the accretion disk (Lee et al. 2002; Yaqoob et al. 2003a). While such lines may be interpreted in terms of a truncated disk (e.g., Done, Madejski, & Życki 2000), they could be due to low-inclination angle disks with a flat radial line emissivity (i.e., intensity per unit area falling off with radius more slowly than r⁻²).

In this paper we address two very specific questions, using the Chandra High Energy Transmission Grating Spectrometer (HETGS; see Markert et al. 1994), which affords the best spectral resolution currently available at 6.4 keV (~39 eV, or ~1860 km s⁻¹ FWHM), namely, for a sample of type I AGNs, what are the energies of the peaks of the Fe K line emission, and are these line cores resolved by Chandra? This information can give important clues about the ionization state of Fe responsible for the line emission, as well as its origin. With Chandra we can measure the peak energies with better precision than ASCA, at least by a factor of 4.

We note that, as a result of the small throughput of the HETGS (especially above ~7 keV), it is very difficult for the grating data to constrain the parameters of any underlying broad Fe Kα line emission. However, in a different study we shall systematically compare the total Fe Kα line emission observed with Chandra and ASCA data and show that, aside from variability in some sources, there is good agreement between the two sets of data. We emphasize that even though the Chandra data for most type I AGNs show narrow Fe Kα line peaks, this by no means indicates that there is no broad Fe Kα line emission.

2. OBSERVATIONS AND DATA

Our study is based on 18 observations of 15 type I AGNs (see Table 1) with z < 0.05 observed with HETGS that were in the Chandra public archives as of 2003 July 1 and had a total, first-order, High Energy Grating (HEG) count rate higher than 0.05 counts s⁻¹. Blazars, BL Lac objects, and AGNs that are intermediate between type I and type II were excluded from the study. Details of all the observations can be found from the Chandra public archive. Three sources were observed more than once: NGC 3516, NGC 5548, and NGC 3783.

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3 See http://cda.harvard.edu:9011/chaser.
| Source          | References | $z^a$ | $E^b$ (keV)          | $I^c$ (10^{-5} photons cm^{-2} s^{-1}) | EW$^d$ (eV) | FWHM$^e$ (km s^{-1}) | $F^f$ (10^{-11} ergs cm^{-2} s^{-1}) | $L^g$ (10^{43} ergs s^{-1}) |
|-----------------|------------|-------|----------------------|----------------------------------------|-------------|----------------------|--------------------------------------|-------------------------------|
| NGC 7314 ....... | 1          | 0.004760 | 6.412 ± 0.010 (6.395–6.430) | 1.7 ± 0.6 (0.7–2.7) | 48 ± 17 (20–76) | 100 f                  | 3.0                                    | 0.15                           |
| NGC 3516(1) ..... | 2          | 0.008836 | 6.398 ± 0.015 (6.389–6.408) | 4.0 ± 0.3 (2.5–5.8) | 140 ± 46 (88–203) | 1290 ± 120 (0–3630) | 2.3                                    | 0.40                           |
| NGC 3516(2) ..... | 2          | 0.008836 | 6.401 ± 0.015 (6.378–6.422) | 3.8 ± 0.3 (2.2–5.8) | 143 ± 56 (83–218) | 3630 ± 2350 (1560–7640) | 2.1                                    | 0.35                           |
| Mrk 509 ........... | 1          | 0.034397 | 6.430 ± 0.020 (6.394–6.461) | 3.1 ± 0.9 (0.9–5.7) | 54 ± 28 (16–99)  | 2820 ± 2400 (0–7710) | 5.3                                    | 14.0                           |
| NGC 5548(1) ....... | 3          | 0.016760 | 6.397 ± 0.015 (6.365–6.462) | 3.1 ± 0.6 (1.5–5.1) | 115 ± 45 (56–189) | 3750 ± 1420 (1250–7610) | 2.4                                    | 1.5                            |
| NGC 5548(2) ....... | 4          | 0.016760 | 6.400 ± 0.015 (6.386–6.414) | 2.1 ± 0.2 (1.2–3.3) | 67 ± 26 (38–105) | 1780 ± 320 (0–3970) | 2.9                                    | 1.8                            |
| 3C 120 ........... | 1          | 0.035010 | 6.415 ± 0.015 (6.392–6.450) | 3.0 ± 0.3 (1.1–5.5) | 61 ± 15 (22–112) | 2000 ± 2000 (0–6770) | 4.4                                    | 10.8                           |
| NGC 4593 .......... | 1          | 0.008301 | 6.403 ± 0.015 (6.349–6.434) | 3.4 ± 0.3 (1.8–8.1) | 80 ± 31 (42–191) | 2140 ± 1230 (310–15920) | 4.1                                    | 0.63                           |
| NGC 3783(1) ....... | 5          | 0.009730 | 6.400 ± 0.015 (6.376–6.420) | 5.0 ± 2.4 (2.4–8.3) | 73 ± 31 (35–121) | 2550 ± 2420 (500–6290) | 6.0                                    | 1.2                            |
| NGC 3783(2) ....... | 6, 7       | 0.009730 | 6.397 ± 0.000 (6.393–6.401) | 4.9 ± 0.6 (4.2–5.6) | 70 ± 40 (60–80)  | 1700 ± 410 (1180–2250) | 6.2                                    | 1.3                            |
| MCG –6-30-15 ....... | 8          | 0.007749 | 6.408 ± 0.005 (6.349–6.454) | 1.6 ± 0.1 (0.4–3.3) | 49 ± 34 (12–101) | 3250 ± 2310 (0–12670) | 3.2                                    | 0.42                           |
| Mrk 279 ........... | 9          | 0.030451 | 6.415 ± 0.025 (6.379–6.521) | 1.9 ± 0.7 (0.7–5.2) | 132 ± 63 (49–361) | 5010 ± 2620 (1100–36980) | 1.3                                    | 2.7                            |
| NGC 4051 .......... | 9          | 0.002336 | 6.419 ± 0.005 (6.910–6.675) | 3.2 ± 1.2 (1.4–25.0) | 191 ± 103 (84–1492) | 6330 ± 7340 (1780–13740) | 1.6                                    | 0.019                          |
| IC 4329A ......... | 9          | 0.016094 | 6.309 ± 0.005 (6.171–6.686) | 11.2 ± 4.4 (1.8–21.3) | 62 ± 35 (10–117) | 15090 ± 12430 (0–37150) | 16.4                                    | 9.4                            |
| F9 ............... | 9          | 0.047016 | 6.373 ± 0.005 (6.203–6.753) | 4.9 ± 0.6 (1.2–17.0) | 216 ± 184 (53–749) | 17040 ± 5590 (2160–92940) | 2.1                                    | 10.6                           |
| Mrk 766 ..........  | 9          | 0.012929 | 6.423 ± 0.005 (6.398–6.456) | 0.7 ± 0.1 (0.1–1.5) | 34 ± 29 (5–73)   | 100 f                   | 2.1                                    | 0.79                           |
| NGC 3227 ........... | 9          | 0.003859 | 6.384 ± 0.005 (6.398–6.456) | 1.1 ± 0.2 (0.0–2.8) | 39 ± 20 (9–99)   | 100 f                   | 2.3                                    | 0.075                          |
| Ark 564 ........... | 10         | 0.024684 | 6.400 f               | 0.3 ± 0.3 (0.0–1.1) | 16 ± 16 (0–59)   | 100 f                   | 2.5                                    | 3.4                            |

Notes.—Chandra HEG data, fitted with a power-law plus Gaussian emission-line model in the 2–7 keV band (for NGC 3516 photoelectric absorption was also included in the model). All parameters (except redshift) were free in the fits, except in the cases of NGC 7314, Mrk 766, NGC 3227 (line width fixed in these cases) and Ark 564 (line energy and width fixed). All parameters are quoted in the source rest frame. Statistical errors are for the 68% confidence level, while parentheses show the 90% confidence level ranges of the parameters. The number of interesting parameters assumed for calculating the statistical errors was equal to the number of free parameters in the Gaussian component of the model. For three, two, and one interesting parameter(s), the corresponding values of $\Delta C$ for 68% confidence are 3.506, 2.279, and 0.989, respectively, and the 90% confidence values of $\Delta C$ are 6.251, 4.605, and 2.706, respectively.

a Redshifts obtained from NASA Extragalactic Database (NED).
b Gaussian line-center energy.
c Emission-line intensity.
d Emission-line equivalent width.
e FWHM, rounded to 10 km s^{-1}.
f $F$ is the estimated 2–10 keV observed flux. The power-law continuum was extrapolated to 10 keV.
g $I$ is the estimated 2–10 keV source-frame luminosity (using the 2–10 keV estimated flux), assuming $H_0 = 70$ km s^{-1} Mpc^{-1} and $q_0 = 0$.

References.—Key for previous publications on the same HEG data: (1) Yaqoob et al. 2003a; (2) Turner et al. 2002; (3) Yaqoob et al. 2001; (4) Kaast et al. 2002; (5) Kaspi et al. 2001; (6) Kaspi et al. 2002; (7) Netzer et al. 2003; (8) Lee et al. 2002; (9) Collinge et al. 2001; (10) Matsumoto, Leighly, & Marshall 2001, available on-line at http://www.pha.jhu.edu/groups/astro/workshop2001/papers/matsumoto_c.ps.
For NGC 3516, observation IDs 2080 and 2431 were combined since they occurred on consecutive days, while observation ID 2482 was treated separately (see also Turner et al. 2002). The two observations of NGC 5548 were treated separately. For NGC 3783, six observations were at first treated separately, but we found that the Fe K line parameters were consistent with no variability, so here we report the results from the ∼850 ks spectrum combined from five snapshots taken during a monitoring campaign but treated this separately from an observation made a year earlier. Detailed results from the monitoring campaign will be presented elsewhere (T. Yaqoob et al. 2004, in preparation; see also Kaspi et al. 2002; Netzer et al. 2003).

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 will focus 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 grating data (combining the positive and negative arms). The mean HEG count rates ranged from 0.087 counts s⁻¹ for the weakest source (NGC 3227) to 1.158 ± 0.006 counts s⁻¹ for the brightest source (IC 4329a). The exposure time ranged from ∼40 to ∼850 ks but was ∼60–100 ks for most of the sources. Background was not subtracted since it is negligible over the energy range of interest (see, e.g., Yaqoob et al. 2003a). Note that the systematic uncertainty in the HEG wavelength scale is ∼433 km s⁻¹ (∼11 eV) at 6.4 keV.⁴

3. SPECTRAL FITTING RESULTS

We used XSPEC version 11.2 (Arnaud 1996) for spectral fitting. Since we are 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. All model parameters will be referred to the source frame. Our method is simply to fit a simple power-law plus Gaussian emission-line model over the 2–7 keV band for each spectrum. NGC 3516 required photoelectric absorption to fit the continuum. In addition, for NGC 7314 the analysis was more complex, involving emission from multiple ionization states of Fe, and has already been described in detail in Yaqoob et al. (2003a). The results presented here for NGC 7314 are for the 6.4 keV line component only (which is unresolved) and have been taken from Yaqoob et al. (2003a), changing only the confidence levels of the quoted statistical errors so that they are consistent with the rest of the sample. For Ark 564 an Fe K emission line was not detected: C decreased by 0.9 (<68% confidence for the addition of one free parameter) when a narrow (FWHM much less than the instrument resolution) emission line at 6.4 keV was added to a power law only. Thus, we obtained upper limits on the equivalent width (EW). A significant Fe K emission line has been detected in Ark 564 with ASCA (Turner et al. 2001). The reason for the nondetection by the HEG is likely to be due to the very steep continuum and the small effective area of the HEG. The line was only weakly detected during recent XMM-Newton observations (Vignali et al. 2004), but the signal-to-noise ratio of those data was still much less than that of the ASCA data.

The case of NGC 3227 and Mrk 766 the detection of an Fe K line was marginal: C decreased by 4.5 and 7.0, respectively, when a narrow Gaussian was added to a power-law model only. In this case we were able to obtain constraints on the line energy and EW, so the Gaussian model had two free parameters. Thus, the lines were detected with less than 90% and less than 95% confidence in NGC 3227 and Mrk 766, respectively. Note that a strong Fe K line has been detected in NGC 3227 by XMM-Newton (Gondoin et al. 2003) and complex Fe K emission has been observed in Mrk 766 by XMM-Newton (Pounds et al. 2003). For the remaining spectra the Gaussian component had three free parameters (line-center energy, width, and intensity). Thus, except for the three cases mentioned above, the model had five free parameters in total, including the continuum slope and normalization.

We used the “goodness” command in XSPEC to assess the goodness of the fits: this command performs Monte Carlo simulations of spectra using the best-fitting model and gives the percentage of the simulated spectra that had a fit statistic less than that obtained from the fit to the real data. A value of 50% is expected if the best-fitting model is a good representation of the data. Values much less than 50% indicate that the data are overparameterized by the model since random statistical fluctuations in the majority of the simulated spectra are not able to produce a fit statistic as low as that obtained from the real data. In the opposite limit, when 100% of the simulated spectra have a fit statistic less than that obtained from the real data, the fit is clearly poor.

Good fits were obtained for all spectra except for NGC 3783(2), the long ∼850 ks observation, in which the continuum is complicated by a warm absorber that affects the spectrum even above 2 keV (see, e.g., Kaspi et al. 2002; Netzer et al. 2003). However, this has little impact on the deduced parameters of the Fe Kα line, which are in fact consistent with those obtained by Kaspi et al. (2002) and Netzer et al. (2003), who used a more complex continuum. The line parameters, including the intensity, are also consistent with those measured from a nonsimultaneous XMM-Newton observation (Reeves et al. 2004), for which a warm absorber was also included in the continuum modeling.

Excluding Ark 564, NGC 3227, and Mrk 766, the Fe Kα line core was detected at a confidence level greater than 3 σ (corresponding to a decrease in C greater than 14.16 when a Gaussian with three free parameters was added to the continuum). Five of these 15 spectra gave goodness values less than 50%. Two of these were close to 50% (NGC 4051: 49%; F9: 47%), so the data are likely not overparameterized. Furthermore, C decreased by 33.2 and 26.6 for NGC 4051 and F9, respectively, when a three-parameter Gaussian model was added to the continuum model. Thus, the line emission was detected at a confidence level greater than 5 and 4 σ in NGC 4051 and F9, respectively, when a three-parameter Gaussian model was added to the continuum model. The goodness value was 40%, still less than 50%, indicating that the signal-to-noise ratio over the entire energy band is poor. The decrease in C when a Gaussian is added to the continuum is 16.8, which still corresponds to a detection at a confidence level greater than 3 σ, for the addition of three free parameters. For NGC 3516(1), the goodness value increases from 10% to 69% when the emission line is removed and the data fitted with a continuum only. The addition of a three-parameter Gaussian to the continuum decreases C by 111.4, confirming what is evident

⁴ See http://space.mit.edu/CXC/calib/hetgcal.html.
Fig. 1.—*Chandra* HEG spectra in the Fe K band from each of the 18 observations of 15 type I AGNs (see Table 1). The data are binned at 0.01 Å for the first 16 spectra shown and 0.02 Å for the last two spectra (NGC 3227 and Ark 564). This can be compared to the HEG spectral resolution, which is 0.012 Å FWHM. The data are combined from the $-1$ and $+1$ orders of the grating. The spectra have been corrected for instrumental effective area and cosmological redshift. Note that these are not unfolded spectra and are therefore independent of the model that is fitted. The statistical errors shown correspond to the 1σ Poisson errors, calculated using eqs. (7) and (14) in Gehrels (1986) to approximate the upper and lower errors, respectively. The solid line corresponds to the continuum model fitted over the 2–7 keV range (extrapolated to 7.5 keV), as described in the text (§ 3). The vertical dotted lines represent (left to right) the rest energies of the following transitions: Fe Kα, Fe xxv forbidden, two intercombination lines of Fe xxv, Fe xxv resonance, and Fe xxvi Lyα. The spectrum for NGC 7314 corresponds to that during a low continuum state, as defined and described in Yaqoob et al. (2003a). Note that apparent narrow features at ~6.35 keV in MCG –6-30-15 and at ~6.55 keV in NGC 3783(2) are detected in one arm of the grating only and are narrower than the spectral resolution; thus, they are not real.
from the spectrum in Figure 1, that the line emission is highly significant and required by the data. Removing the emission line and fitting a continuum only, in the case of NGC 5548(1), increases the goodness value from 7% to 18%, still below 50%. However, the addition of a three-parameter Gaussian to the continuum decreases $C$ by 35.0, indicating that the Fe K line is detected at a confidence level greater than 5 $\sigma$. The low values of the goodness parameter are due to poor signal-to-noise ratio over the whole energy band since a simple two-parameter continuum gives a goodness value much less than 50%.

Although the Fe K line consists of two components (K$_{\alpha 1}$ and K$_{\alpha 2}$, separated by 13 eV), we modeled it as a single Gaussian, since it was shown in Yaqoob et al. (2001) that with the spectral resolution of the HEG, there is a negligible impact on the measured line width. Some broadening may also result
from the presence of line emission from more than one ionization state of Fe. However, we do not interpret the measured FWHM velocities literally. Furthermore, the use of a single Gaussian (without any attempt to model the underlying broad Fe Kα emission) also has a negligible impact on the measured center energy of the core, the line intensity, and EW (see Yaqoob et al. 2001). Again, we only interpret the line intensity and EW qualitatively. Furthermore, one of the reasons for measuring the width of the line core is to obtain clues about any underlying broad Fe Kα line component.

The best-fitting emission-line parameters for each spectrum are shown in Table 1 (as well as extrapolated 2–10 keV fluxes and luminosities). Note that since the models were fitted by first folding through the instrument response before comparing with the data, the derived line parameters do not need to be corrected for instrumental response. In order that the
results can be used for future statistical analyses, the statistical errors shown correspond to 68% confidence ($\Delta C = 3.506, 2.279$, or $0.989$, depending on whether there were three, two, or one parameter[s] free in the Gaussian component). However, as a more conservative measure, the 90% confidence range for each line parameter is also given in Table 1. Figure 1 shows each of the 18 spectra in the Fe K region, corrected for instrumental efficiency and cosmological redshift. The spectra are binned at 0.01 Å, similar to the HEG spectral resolution of 0.012 Å, so broad features are not readily discernible in this representation.

4. PROPERTIES OF THE CORE OF THE Fe K LINE EMISSION

Figure 2 shows joint, 99% confidence contours of the line intensity versus line-center energy for 13 of the 18 spectra, and Figure 3 shows the 99% confidence contours of the line EW versus FWHM width for the same spectra. Excluded were Mrk 766, NGC 3227, and Ark 564 (since the constraints on the line parameters are poor), the short, first observation of NGC 3783 (since the later observation had ~20 times the exposure time), and NGC 7314 (which has complex Fe K emission from multiple ionization states; see Yaqoob et al. 2003a).

Figures 2 and 3 show the results for the 11 sources, split into two groups. Group 1 (Figs. 2a and 3a) is comprised of NGC 3516, Mrk 509, NGC 5548, 3C 120, NGC 3783, and MCG ~6-30-15. Group 2 (Figs. 2b and 3b) is comprised of NGC 4593, Mrk 279, NGC 4051, IC 4329a, and F9. Roughly speaking, group 1 AGNs have more prominent narrow Fe K line cores than group 2, as evidenced by the larger contours for group 2. In fact, for NGC 4593 and NGC 4051 the 99% contours could not be well constrained because when the Gaussian is very broad, there is a lot of interaction between the line width and the continuum slope, particularly if there is a reflection continuum, which we have not modeled here. Therefore, we constructed additional contours for all the sources by fixing the power-law slope at the best-fitting value for each source. These contours are shown with dashed lines in Figures 2b and 3b. For the group 1 sources, the differences between the two sets of contours were negligible so they are not shown for the sake of clarity.

We emphasize that the size of the 99% contours is not simply a function of signal-to-noise ratio of the data. To illustrate this point, we have included a group 1 contour (NGC 3516, first observation) in the group 2 plots. We can compare this with F9, which has the largest contours of all 11 sources. Now, the total number of photons in the 5–7 keV band in the NGC 5548 and F9 spectra is 1240 and 1146, respectively. Thus, the significant differences in the sizes of the contours for the two sources are due to intrinsic differences in the emission-line profile, not just signal-to-noise ratio. Furthermore, since NGC 5548 and F9 have the lowest signal-to-noise ratio spectra of the 11 sources, we can conclude that the relative differences in the contours in general may be due to intrinsic differences in the line shape.

Physically, what this means is that the group 1 sources have Fe K line emission, which at the very peak is dominated by a low-velocity emission component that is near the rest energy of Fe I Kα. This does not, of course, mean that group 1 sources do not necessarily have broad Fe Kα line components. Indeed, MCG ~6-30-15 is in group 1, but it has the strongest and broadest Fe Kα line yet observed in an AGN. It simply means that our single-Gaussian fits are picking up a narrow component at ~6.4 keV that stands prominently

![Figure 2](image-url)

**Fig. 2.**—(a) Joint 99% confidence contours of the Fe Kα emission line core intensity vs. line-center energy obtained from Gaussian fits to the line as described in the text, for eight observations of six AGNs: NGC 3516 (black), Mrk 509 (red), NGC 5548 (green), 3C 120 (blue), NGC 3783 (magenta), and MCG ~6-30-15 (orange). See also Table 1 and Fig. 3. Dotted contours are for the same source but from a different observation (the dotted contours are for the lowest signal-to-noise ratio spectrum of the pair in each case). Note that the very smallest contour (magenta) is from the ~850 ks observation of NGC 3783. The first observation of NGC 3783 was excluded from the plot because it is has a factor of ~20 less exposure time. Also excluded were NGC 7314 (Fe K line emission was very complex) and Mrk 766, NGC 3227, and Ark 564, which all had insufficient signal-to-noise ratio to obtain well-constrained contours. (b) Same as (a), but for five more AGNs: NGC 4593 (black), Mrk 279 (red), NGC 4051 (green), IC 4329a (blue), and F9 (orange). Also shown here is the 99% contour for NGC 5548(1) (magenta); the smallest contour in the plot to compare with the contour of F9. These two data sets have a similar number of counts in the 5–7 keV spectra, but the size and shape of the contours are completely different. This shows that the differences in the size and shape of the contours in general reflect intrinsic differences in the line profile shapes. The dashed contours were obtained by fixing the power-law continuum slope after finding the best fit because closed contours could not be obtained otherwise for NGC 4593 (black) and NGC 4051 (green). For the sources in (a), the contours obtained by freezing the continuum slopes at the best-fitting values were not significantly different from the fits with all parameters free, so they are not shown for clarity.
avoid bias due to the very deep, $\sim$850 ks exposure of this AGN, we obtained 6.404 ± 0.005 keV. Here, for the calculation of the weighted mean of any quantity with asymmetric errors, we simply assume symmetric errors, using the largest 68% confidence error in Table 1. The weighted mean FWHM of the Fe Kα line cores for the 14 data sets for which it could be measured is 1850 ± 360 km s$^{-1}$. Without NGC 3783(2) it is 2380 ± 760 km s$^{-1}$. For the eight group 1 observations of six AGNs (see Figs. 2a and 3a), the weighted mean line-center energy and FWHM are 6.398 ± 0.003 keV and 1756 ± 366 km s$^{-1}$, respectively. For the five observations of the five sources in group 2 (see Figs. 2b and 3b), the weighted mean line-center energy and FWHM are 6.406 ± 0.023 keV and 5831 ± 4046 km s$^{-1}$, respectively. At 99% confidence, the Chandra HEG resolves the narrow component of the Fe Kα emission in three group 1 spectra [NGC 3516(2), NGC 3783(2), and NGC 5548(1)] and three group 2 spectra (Mrk 279, NGC 4051, and F9). Interestingly, in NGC 3516 and NGC 5548 (which have multiple observations), the line is resolved in the lower signal-to-noise ratio spectrum in each case. In each source the continuum level appears to be similar for the pair of observations. Therefore, there appears to be real variability in the line width on a timescale of months to years, which indicates a change in the dominant distance of the line emission relative to the putative central black hole. Alternatively, it may be that there is a variable broad accretion disk component affecting the measured width of the line core.

Figure 2a shows that for NGC 3516, NGC 3783, and NGC 5548 the 99% contours of line intensity versus center energy are less than $\sim$80 eV wide and are fairly symmetrical about 6.400 keV. Thus, in these AGNs, the narrow Fe Kα component detected by the HETGS is predominantly from distant matter. The FWHM contours in Figure 3 suggest an origin at the location of the optical BLR and/or beyond (see also Yaqoob et al. 2001; Kaspi et al. 2002; Page, Davis, & Salvi 2003). Because of the symmetry of the contours around 6.400 keV, the 99% confidence bounds imply that most of the Fe must be less ionized than Fe xv or so, with Fe i being the most likely ionization state. For 3C 120 and Mrk 509, the 99% intensity versus energy contours are $\sim$70 and $\sim$90 eV wide, respectively, and both contours are centered significantly above 6.400 keV (by $\sim$25 eV). For these two sources, the most dominant ionization stage is likely to be Fe xvii or so, but the 99% contours do not rule out anything in the range from Fe i to Fe xix. We note that 3C 120 and Mrk 509 are two of the most luminous sources in the sample (see Table 1) so a higher ionization state for the line-emitting matter may be commensurate with this (see, e.g., Nandra et al. 1997b). Thus, not only is the origin of the entire Fe Kα line emission in these two sources controversial (3C 120, Zdziarski & Grandi 2001; Mrk 509, Pounds et al. 2003; Page et al. 2004; De Rosa et al. 2004), but the origin of the peak emission is also ambiguous.

The last source, MCG −6−30−15, has the widest intensity versus energy contour ($\sim$170 eV) in group 1, so the narrow Fe Kα line component in this case clearly is being affected by the underlying broad line. Since the contour is symmetric about 6.4 keV, the ionization state is likely to be low (but the 99% upper limit allows ionization states up to Fe xviii). We note that the EW of the narrow-line component is about the same as that obtained by Wilms et al. (2001) and Ballantyne, Vaughan, & Fabian (2003), who included it in a complex broad-line plus narrow-line model applied to XMM-Newton data.

Strictly speaking, in all six of the group 1 sources, we cannot rule out higher ionization states than mentioned, as a
result of the possibility of gravitational redshifts affecting the line peak. However, it seems unlikely that the dominant ionization stage of Fe and the gravitational redshifting would conspire to give a center energy so close to 6.4 keV in four of the six group 1 sources.

Of the five group 2 AGNs, the Fe Kα line cores in three of them are resolved (Mrk 279, NGC 4051, and F9). This, along with the fact that the 99% contours in both center energy and line width (Figs. 2b and 3b, respectively) are very wide, implies that the line cores in these sources are clearly dominated by a broad line. However, the fact that the line-center best-fitting values are still close to 6.4 keV, as well as the presence of asymmetry in the contours (compared to group 1), means that there is still an important contribution from matter that is in the outer accretion disk or far from it. In NGC 4593 and IC 4329a the line peak is not resolved and is stronger than in the other three group 2 sources, but not as dominant over the broad Fe Kα emission as it is for the group 1 sources.

Figure 4 shows the ratios of the spectral data to the simple fitted continua, in the 3–8 keV band for the group 2 sources. Note that MCG –6-30-15 is a group 1 source but still has a strong broad Fe K line component. However, it is not shown in Figure 4 since a similar plot has already been shown by Lee et al. (2002) and discussed at length. The data in Figure 4 have been binned at 0.04 Å so the broad structure of the Fe K line emission in these sources is more readily apparent than in Figure 1. However, we find that, except for IC 4329a, the signal-to-noise ratio and bandpass of the data are insufficient to provide useful constraints on physical models from spectral fitting. In any case, this is beyond the scope of the present paper, in which we are concerned with measurements of the line cores. IC 4329a is by far the brightest AGN in the sample, and detailed modeling of the complex Fe K line emission apparent in Figure 4 is presented in McKernan & Yaqoob (2004). Here we simply note that one interpretation of the data for IC 4329a is that the higher energy peak in the Fe K complex is due to Fe x x v i Lyα emission. NGC 7314 is the only other source in this Chandra sample with a statistically significant peak near the energy expected for Fe x x v i Lyα (see Yaqoob et al. 2003a). XMM-Newton data for MCG –6-30-15 show structure in the line emission above 6.4 keV that could be interpreted as either Fe He-like resonance absorption at ∼6.7 keV or Fe H-like emission at ∼6.9 keV (Fabian et al. 2002). The HEG data are rather ambiguous. He-like absorption may be present, but the signal-to-noise ratio is too poor (see also Lee et al. 2002). In our HEG sample, there is marginal evidence for a peak near ∼6.9 keV in 3C 120, NGC 4593, F9, and Mrk 766. Aside from NGC 7314, emission from He-like Fe is not evident from any of the other spectra. It is also difficult to rule out He-like resonance absorption in cases where there is an underlying broad Fe K emission line because one does not know how much broad-line emission there is at the resonance energy if some of it has been absorbed.

If the core of the Fe Kα line originates in an accretion disk, we can obtain some simple constraints on the inclination angle and outer radius of emission given that the two Doppler peaks from the outer radius of emission are both contained within the FWHM as measured with our Gaussian fits. Note that the line profile integrated between two radii may not actually have discernible Doppler peaks, but in the dispersion of the energies of the red and blue Doppler horns at the outer radius still sets a firm lower limit on the overall line width, assuming azimuthal symmetry of the line emission. Using a simple Schwarzschild

![Fig. 4.—Ratios of HEG data to a simple power-law continuum model (fitted as described in §3) for five AGNs in Fig. 1 and Table 1, which show evidence of broad and/or complex Fe K line emission. MCG –6-30-15 is not shown, since a similar plot has already been shown in Lee et al. (2002). The data are binned at 0.04 Å, coarser than the HEG spectral resolution (0.012 Å FWHM). The data are combined from the –1 and +1 orders of the grating. The spectra have been corrected for instrumental effective area and cosmological redshift. The statistical errors shown correspond to the 1σ Poisson errors, calculated using eqs. (7) and (14) in Gehrels (1986) to approximate the upper and lower errors, respectively. The vertical dotted lines represent (left to right) the rest energies of the following transitions: Fe i Kα, Fe xxv forbidden, two intercombination lines of Fe xxv, Fe xxv resonance, and Fe xxvi Lyα.](image-url)
geometry and the approximations in Yaqoob et al. (2003a), the condition that the line centroid is shifted by less than $\epsilon = \Delta E/E_0 = (r/rg) > 2[1-(1-\epsilon)^{-2}]^{-1}$, where $r_g = GM/c^2$. For $\Delta E = 50$ eV and $E_0 = 6.4$ keV, $r > 129r_g$. For the worst case, in which the He-like Fe K line is shifted down to 6.4 keV ($\Delta E = 280$ eV, $E_0 = 6.7$ keV), $r > 24r_g$. Now, for a given outer radius, if the disk inclination is too large, the line will be too broad. The separation of the Doppler peaks from the emission at the outer radius must be less than the FWHM, so $2(r_g/r)^{1/2} \sin \theta < \text{FWHM}/c$ (see, e.g., Yaqoob et al. 2003a). Combining this with the energy shift condition gives $\sin \theta < (\text{FWHM}/c)[2[1-(1-\epsilon)^{-2}]^{-1}]^{1/2}$. Thus, for the group 1 cases in which the lines are unresolved, using FWHM = 1860 km s$^{-1}$ and $\Delta E = 10$ eV gives a very tight constraint of $\theta < 4.5\times$. For FWHM = 10, 000 km s$^{-1}$ (more appropriate for 3C 120 and Mrk 509) and $\Delta E$ in the range from 25 to 280 eV, the upper limit on $\theta$ is in the range from 15.5 to 4.6, respectively. The constraints on the group 2 sources are obviously much looser. In general, if there is a significant disk contribution to the Fe K$\alpha$ line core, aside from the small inclination angle, there must be significant line emissivity at large radii. This would be more easily achieved if the X-ray continuum source illuminating the disk were extended over the disk (for example, the corona) rather than localized at the center of the system. Whether the continuum source is centrally localized or extended, a geometry in which the disk becomes flared at large radii would also help.

Table 1 and Figure 3 show that the EWs of the Fe K$\alpha$ line core are typically in the range ~40–200 eV. An EW of 40 eV can easily be produced by a column density of $10^{23}$ cm$^{-2}$, covering 35% of the sky as seen from the X-ray continuum source, values that are reasonable for the optical BLR in NGC 5548 (see discussion in Yaqoob et al. 2001). A line core EW of 40 eV could also conceivably be produced by the outer regions of an accretion disk viewed at small inclination angles (see, e.g., George & Fabian 1991). However, values of EW at the higher end of the measured range (~100–200 eV) require supersolar iron abundances or anisotropic illumination of the line-emitting matter by the X-ray continuum. Line emission from a parsec-scale torus structure, which has been invoked in AGN unification schemes, could also help in accounting for the larger EWs since it could subtend a substantial solid angle at the continuum source and easily contribute another ~50 eV to the core EW. If the torus is optically thick, a Compton reflection continuum is predicted, commensurate with the EW of the line emission. In principle, this would be a useful observational diagnostic. However, uncertainties in the Compton thickness of the torus, the iron abundance, the contribution to the reflection continuum from the outer disk, and the amount of line contribution from the (optically thin) BLR, not to mention the measurement uncertainties in the reflection continuum itself, make it difficult to draw robust conclusions from correlating the line EW with the strength of the reflection continuum. The situation is sufficiently complicated that these tests must be done on a source-by-source basis and is beyond the scope of the present paper. We note also that the precision of our new measurements of peak energy, core FWHM, and EW will allow more stringent tests of alternative models of the origin of the Fe K$\alpha$ line emission than has hitherto been possible (see, e.g., Sulentic et al. 1998; Elvis 2000).

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REFERENCES

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. Jacoby & J. Barnes (San Francisco: ASP), 17

Ballantyne, D. R., Vaughan, S., & Fabian, A. C. 2003, MNRAS, 342, 239

Collinge, M. J., et al. 2001, ApJ, 557, 2

De Rosa, A., Piro, L., Matt, G., & Perola, G. C. 2004, A&A, 413, 895

Done, C., Madejski, G. M., & Zgajner, P. T. 2000, ApJ, 536, 213

Elvis, M. 2000, ApJ, 545, 63

Fabian, A. C., Iwasawa, K., Reynolds, C. S., & Young, A. J. 2000, PASP, 112, 1145

Fabian, A. C., et al. 2002, MNRAS, 335, L1

Gehrels, N. 1986, ApJ, 303, 336

George, I. M., & Fabian, A. C. 1991, MNRAS, 249, 352

Gondoin, P., Orr, A., Lomb, D., & Siddiqui, H. 2003, A&A, 397, 883

Kaastra, J. S., et al. 2002, in ASP Conf. Ser. 290, Active Galactic Nuclei: From Central Engine to Host Galaxy, ed. S Collin, F. Combes, & I. Shlosman (San Francisco: ASP), 101

Kaspi, S., et al. 2001, ApJ, 554, 216

——. 2002, ApJ, 574, 643

Lee, J. C., Iwasawa, K., Houck, J. C., Fabian, A. C., Marshall, H. L., & Canizares, C. R. 2002, ApJ, 570, L47

Lubiszewski, P., & Zdziarski, A. A. 2001, MNRAS, 323, L37

Markert, T. H., Canizares, C. R., Dewey, D., McGuirk, M., Pak, C., & Shattenburg, M. L. 1994, Proc. SPIE, 2280, 168

McKernan, B., & Yaqoob, T. 2004, ApJ, in press

Nandra, K., George, I. M., Mushotzky, R. F., Turner, T. J., & Yaqoob, T. 1997a, ApJ, 477, 602

——. 1997b, ApJ, 488, L91

Netzer, H., et al. 2003, ApJ, 599, 933

Page, K. L., O’Brien, P. T., Reeves, J. N., & Turner, M. J. L. 2004, MNRAS, 347, 316

Page, M. J., Davis, S. W., & Salvi, N. J. 2003, MNRAS, 343, 1241

Perola, G. C., Matt, G., Cappi, M., Fiore, F., Guainazzi, M., Marsichi, L., Petrucci, P. O., & Piro, L. 2002, A&A, 389, 802

Petrucci, P. O., et al. 2002, A&A, 388, L5

Pounds, K. A., Reeves, J. N., Page, K. L., Wynn, G. A., & O’Brien, P. T. 2003, MNRAS, 342, 1147

Reeves, J. N. 2002, in ASP Conf. Ser. 290, Active Galactic Nuclei: From Central Engine to Host Galaxy, ed. S Collin, F. Combes, & I. Shlosman (San Francisco: ASP), 35

Reeves, J. N., Yaqoob, T. K., George, I. M., Mushotzky, R. F., Turner, T. J., & Yaqoob, T. 2004, ApJ, in press (astro-ph/0310820)

Reynolds, C. S., & Nowak, M. A. 2003, Phys. Rep., 377, 389

Sulentic, J. W., Marziani, P., Swift, T., Calvani, M., & Dultzin-Hacyan, D. 1998, ApJ, 501, 54

Turner, T. J., Romano, P., George, I. M., Edelson, R., Collier, S. J., Mathur, S., & Peterson, B. M. 2001, ApJ, 561, 131

Turner, T. J., et al. 2002, ApJ, 574, L123

Vignali, C., Brandt, W. N., Boller, Th., Fabian, A. C., & Vaughan, S. 2004, MNRAS, 347, 854
Weaver, K. A., Gelbord, J., & Yaqoob, T. 2001, ApJ, 550, 261
Wilms, J., Reynolds, C. S., Begelman, M. C., Reeves, J., Molendi, S., Staubert, R., & Kendziorra, E. 2001, MNRAS, 328, L27
Yaqoob, T., George, I. M., Kallman, T. R., Padmanabhan, U., Weaver, K. A., & Turner, T. J. 2003a, ApJ, 596, 85
Yaqoob, T., George, I. M., Nandra, K., Turner, T. J., Serlemitsos, P. J., & Mushotzky, R. F. 2001, ApJ, 546, 759
Yaqoob, T., McKernan, B., Kraemer, S. B., Crenshaw, D. M., Gabel, J. R., George, I. M., & Turner, T. J. 2003b, ApJ, 582, 105
Yaqoob, T., Padmanabhan, U., Dotani, T., & Nandra, K. 2002, ApJ, 569, 487
Zdziarski, A. A., & Grandi, P. 2001, ApJ, 551, 186