

New *Chandra* Results on Seyfert I Galaxies: Fe-K lines

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Abstract. We present measurements of the Fe-K α line for nine Seyfert I galaxies using *Chandra* High Energy Transmission Grating Spectrometer (*HETGS*) data. The centroid energies are narrowly dispersed (6.403 ± 0.062 keV) and indicate an origin of the line cores in cold matter. If all the lines in this sample were the peaks of a relativistically broadened disk line, it would require unrealistically fine tuning. However, at least three of the nine AGN clearly show a complex Fe-K α line with an underlying broad component, possibly from a disk. In the others, an apparently narrow Fe-K α line (even if it is resolved by *Chandra*) may still be due to the peak of a disk line. To distinguish this scenario from an origin in distant matter requires variability information.

1. Introduction

The Fe-K α emission lines in type 1 AGN can be complex, consisting of a broad ($\sim 10,000 - 100,000$ km/s FWHM) and/or a narrow ($< 10,000$ km/s FWHM) component (e.g. Yaqoob et al. 2002). The broad component probably originates from the accretion disk, having suffered severe Doppler and gravitational energy shifts in the inner disk (e.g. see review by Fabian et al. 2000) and has been clearly observed by *ASCA*. *Chandra* and *XMM* are revealing that a narrow-line (NL) component is quite common in type 1 AGN (Reeves et al. 2001; Yaqoob et al. 2001a; Yaqoob et al. 2001b; Kaspi et al. 2001; Pounds et al. 2001; Turner et al. 2002, Fang et al. 2002), often superimposed on top of a broad component. Even with *Chandra*, the NL component has only been resolved in two cases at $> 99\%$ confidence (NGC 3783 [Kaspi et al. 2002] and MCG -6-30-15 [Lee et al. 2002]). Interpreting the line width in NGC 3783 (1720 ± 360 km/s FWHM) as the result of Doppler shifts in a spherical gas distribution with Keplerian velocity places its origin in between the BLR and NLR. However, variability information is required to truly constrain the origin of the line. The NL observed in MCG -6-30-15 has a width of ~ 3600 km/s FWHM (high flux state) but it cannot arise from distant matter, as demonstrated by the rapid variability of the line (Lee et al. 2002). Thus, some of the narrow lines observed by *Chandra* could be the cores of an underlying broad disk line.

Here we examine the data from nine Seyfert I galaxies observed by the *Chandra HETGS*. We present the most precise measurements to date of the peak energies and widths of the line cores. By comparing the confidence contours of the equivalent widths (EW) versus FWHM velocity widths and line intensity

versus peak energy, we can infer important differences about the origin of the lines in different sources.

2. Method

The analysis method was similar to that used in Yaqoob et al. (2001a) except that the data were reprocessed using *ciao* 2.1.3 and CALDB version 2.7, according to recipes described in *ciao* 2.1.3. The *HETGS* is composed of the *High Energy Grating* (HEG) and the *Medium Energy Grating* (MEG) and we used only the HEG data since it has the best energy resolution (1860 km/s FWHM at 6.4 keV) in the Fe-K α region. We fitted the HEG data with a model of simple power law plus a Gaussian from 2 keV to 7 keV. All parameters, including the line width, were allowed to float. The power law slope was then frozen at the best-fit value. Using just the 5 to 7 keV data, the joint confidence contour plots of the line intensity versus the line energy, and EW versus the FWHM were made. These are shown in Figures 1 and 2 respectively. The best-fitting line parameters, with statistical errors at 90% confidence for one interesting parameter, are shown in Table 1. Note that the results obtained when the power-law slope is allowed to float are similar (full details will be presented elsewhere).

Table 1. Power law plus Gaussian fits to the *Chandra* (HEG) data.

Source	E ^a (keV)	I ^b (10 ⁻⁵ photons cm ⁻² s ⁻¹)	EW ^c (eV)	FWHM (km/s)
NGC 3516	6.400 ^{+0.008} _{-0.010}	4.3 ^{+1.3} _{-1.1}	162 ⁺⁴⁷ ₋₄₁	1390 ⁺¹⁶⁴⁰ ₋₁₃₉₀
NGC 3783	6.399 ^{+0.013} _{-0.013}	5.3 ^{+2.2} _{-1.8}	79 ⁺³³ ₋₂₇	2640 ⁺²²⁰⁰ ₋₁₂₆₅
NGC 5548	6.397 ^{+0.021} _{-0.022}	3.0 ^{+1.5} _{-1.3}	106 ⁺⁵³ ₋₄₆	3650 ⁺²⁶⁹⁰ ₋₂₀₀₀
3C 120	6.414 ^{+0.019} _{-0.016}	3.0 ^{+1.8} _{-1.4}	61 ⁺³⁶ ₋₂₉	2090 ⁺²⁸⁶⁰ ₋₁₉₂₀
Mkn 509	6.431 ^{+0.027} _{-0.023}	2.8 ^{+1.9} _{-1.7}	45 ⁺³⁰ ₋₂₇	2740 ⁺²⁶³⁰ ₋₂₇₄₀
NGC 4593	6.402 ^{+0.014} _{-0.020}	3.2 ^{+1.5} _{-1.3}	73 ⁺³⁵ ₋₂₉	2140 ⁺⁴⁰³⁰ ₋₁₄₈₀
NGC 4051	6.417 ^{+0.035} _{-0.031}	2.7 ^{+1.6} _{-1.3}	147 ⁺⁸⁶ ₋₆₉	5190 ⁺⁵⁵³⁰ ₋₃₅₄₀
F 9	6.424 ^{+0.031} _{-0.089}	2.2 ^{+2.9} _{-1.1}	86 ⁺¹¹³ ₋₄₃	4040 ⁺¹⁵⁷²⁰ ₋₁₈₄₀
3C 273	6.348 ^{+0.052} _{-0.048}	5.5 ^{+5.9} _{-1.5}	32 ⁺³⁵ ₋₉	4610 ⁺⁸⁰⁵⁰ ₋₄₁₇₀

Statistical errors are for 90% confidence for one interesting parameter ($\Delta C = 2.706$). ^a Center energy of Gaussian line. ^b Line Intensity. ^c Equivalent Width.

3. Centroid Energies of the Fe-K lines

In Figure 1 we show the line intensity versus line center energy confidence contours. Note that the dotted line is at 6.4 keV and all the contours intersect it, at least at the 99% confidence level. Due to the superb energy resolution of the *Chandra* HEG, the 90% statistical errors on the line energy can be as small as 10 eV. The most tightly constrained contours are those of NGC 3516, which has an exposure time of 100 ks and a comparatively low (2–10 keV) flux of 2.5×10^{-11} erg cm⁻² s⁻¹. The weighted mean centroid energy of the line detected in the nine Seyfert galaxies is 6.403 ± 0.062 keV. The small dispersion is quite remarkable. If all these lines were from a disk, the disk parameters would

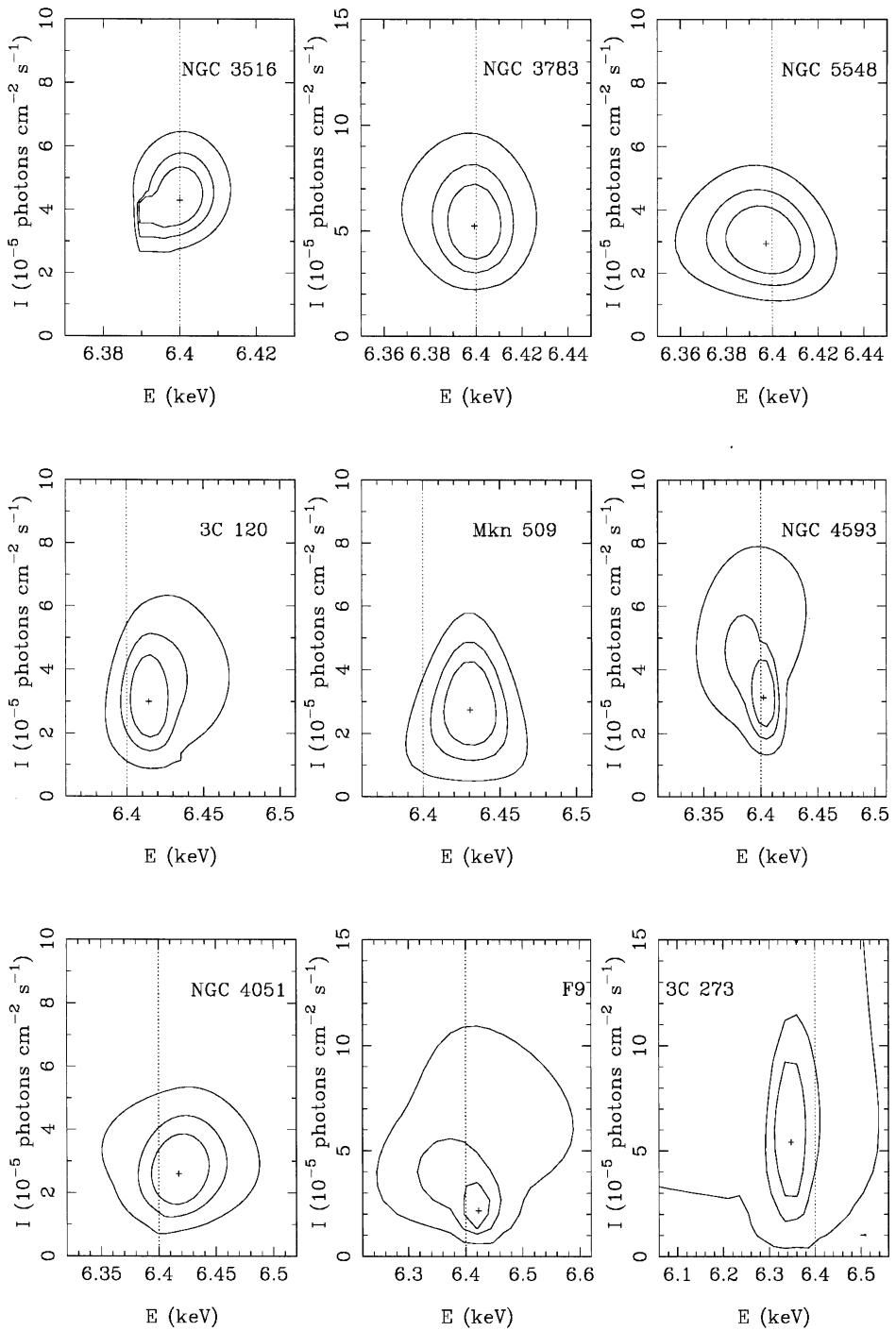


Figure 1. HEG confidence contours (68%, 90%, 99%) of Fe-K line of Line Intensity versus Line Energy for the nine AGN.

need to be finely tuned. Whatever the origin of the lines, the cores observed by the HEG are formed in cold Fe.

The detailed shapes of the contours carry additional information about the line profiles. Comparing the contours of NGC 5548 and F 9, we see a clear and marked difference in the shapes of their contours. However, they have a similar signal-to-noise ratio (SNR) as evidenced by the number of photons in the 5 to 7 keV band. Thus, the difference in the contours are due to the intrinsic differences in their line profiles and *are not due to SNR effects*. The broader contours of F 9 indicate a complex line, consistent with the line profile in Yaqoob et al. (2001b). *RXTE* data, simultaneous with the *Chandra* observation for F 9, confirms the presence of a broad He-like Fe-K α component (see Yaqoob & Padmanabhan 2003; hereafter YP03). The SNR in the other seven AGN is greater than that of NGC 5548 and F 9. Therefore, we can infer that the differences in the contours of *all* the AGN are not due to SNR effects, except for 3C 273 where the EW of the line is much less than in the other sources. The contours of NGC 3516, NGC 3783, 3C 120 and MKN 509 are very similar to that of NGC 5548 and those of NGC 4051 and NGC 4593 are similar to that of F 9.

4. EW versus FWHM

In Figure 2 the EW versus FWHM confidence contours are shown. Note that the dotted line on these plots shows the FWHM resolution of the HEG (1860 km/s at 6.4 keV for $z = 0$) at the measured, *observed* peak energy of each line (that is, accounting for redshift). Again, comparing NGC 5548 and F 9 (since they have similar SNR), we find that their contours have very different shapes. The contours of NGC 5548 show the 99% confidence level (CL) FWHM bound at $\sim 10,000$ km/s with the line peak unresolved at the 99% CL. On the other hand, in F 9 the FWHM extends out $\sim 60,000$ km/s at the 99% CL (which is off the scale in Figure 2 but can be seen in YP03). F 9 also shows the only resolved peak at the 99% CL in this sample. Thus, the lines in F 9 and NGC 5548 are very clearly different, with the line in F 9 definitely accompanied by a broader component and the line in NGC 5548 comparatively narrower. The FWHM contours of NGC 3516, NGC 3783, 3C 120, and Mkn 509 are similar to that of NGC 5548. NGC 4593, NGC 4051 and F 9 all show clear underlying broad components. Except for F 9, all the Fe-K α lines in the sample, show an unresolved peak at the 99% CL.

Lee et al. (2002) found that in a *Chandra* observation of MCG -6-30-15, the HEG Fe-K α line was resolved, with a best-fit FWHM width of 11,000 km/s (time-averaged). Considering only the high flux state, the line was resolved with a best-fit FWHM width of 3600 km/s. However, this line was shown to be variable on short time scales (hundreds of seconds). Thus, this line is most probably the core of a very peaky disk line, since it is impossible for either the putative obscuring torus, or even the BLR to respond to continuum variations so quickly. This demonstrates that even the AGN in our sample which show 99% CL FWHM contours less than 15,000 km/s may have Fe-K α line cores which are from a disk and not from more distant matter.

On the other hand, for the dispersion in the line centroid energies to be so small, the radial emissivity of the disk must be very flat *and* the disk inclination

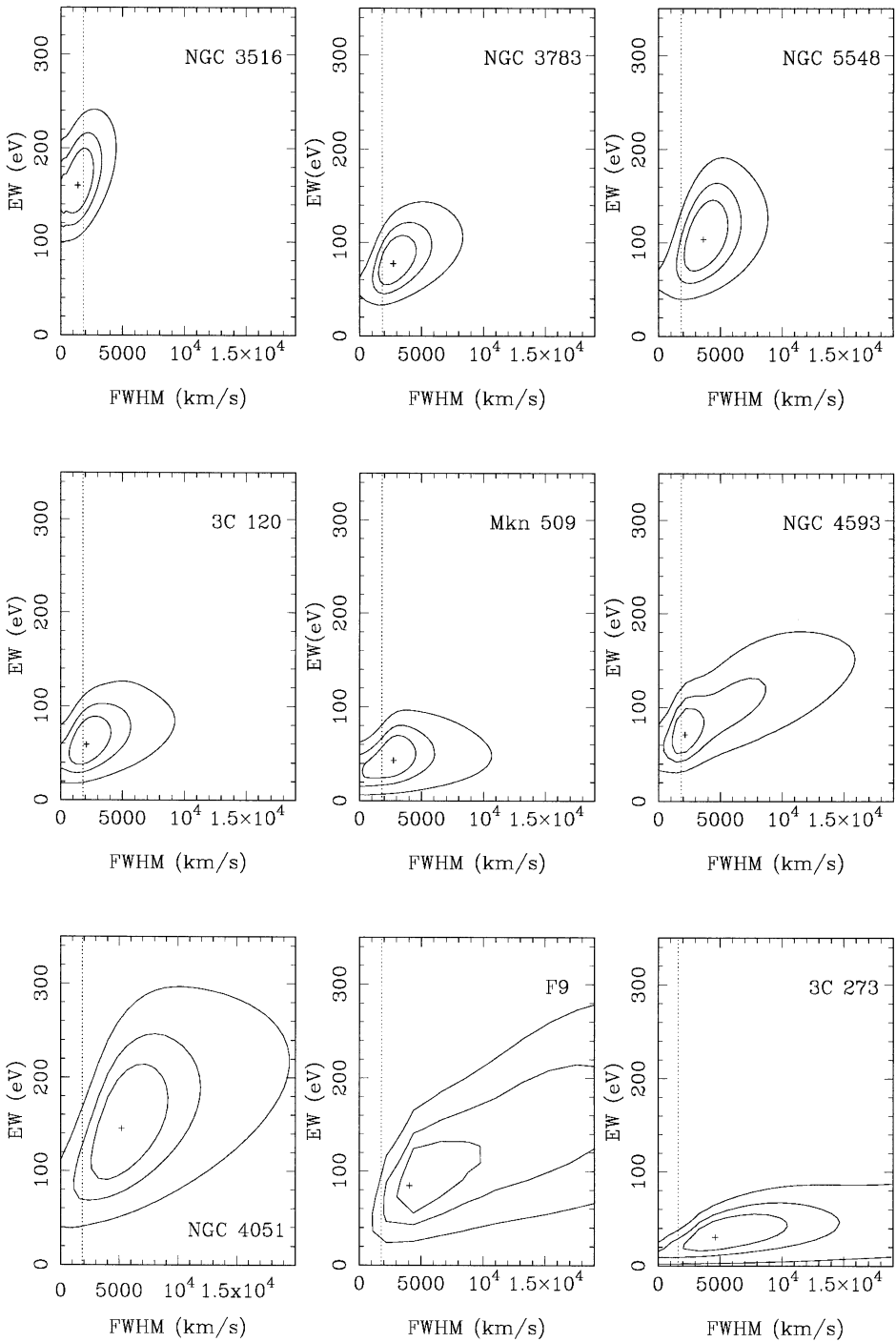


Figure 2. HEG confidence contours (68%, 90%, 99%) of Fe-K line EW vs. FWHM of the nine AGN.

angles must be small and narrowly distributed (almost face-on). To determine the dominant contribution to the line core (disk or distant matter) requires variability information. The EWs of the line cores range from ~ 30 eV to ~ 150 eV. When there is an additional broad line, as measured by a higher throughput mission (e.g. *RXTE*; see YP03), the total EW can easily exceed twice this value. However, an interpretation of the EWs requires detailed physical modeling which will be presented elsewhere.

5. Conclusions

Measurements of the Fe-K α line centroid energy and width for nine Seyfert I galaxies using the best energy resolution available show that the centroid energies of the line cores are narrowly dispersed (6.403 ± 0.062 keV) and are consistent with a dominant contribution to the line core from cold matter. Three sources (NGC 4051, NGC 4593 and F 9) clearly show a complex Fe-K α line with an underlying broad, relativistic component. In the remaining AGN (except 3C 273), although the FWHM is $< 11,000$ km/s (99% CL), we cannot rule out the line core still coming from a disk (as opposed to originating in distant matter). However, the small dispersion in the peak energy requires a very flat radial emissivity law and a narrowly distributed disk inclination angle. Variability information is required to determine the origin of the line core in these cases.

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