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The Case for General Relativistic Effects in the Fe Kα Profile of an Active Galaxy

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ABSTRACT

We present results from a simultaneous *Chandra* HETG and *XMM-Newton* observation of NGC 3516. We find evidence for several narrow components of Fe Kα along with a broad line. We consider the possibility that the lines arise in an blob of material ejected from the nucleus with velocity $\sim$ 0.25c. We also consider an origin in a neutral accretion disk, suffering enhanced illumination at 35 and 175 R_g, perhaps due to magnetic reconnection. The presence of these narrow features indicates there is no Comptonizing region along the line-of-sight to the nucleus. This in turn is compelling support for the hypothesis that broad Fe Kα components are, in general, produced by strong gravity.

Subject headings: galaxies: active – galaxies: individual (NGC 3516) – galaxies: nuclei – galaxies: Seyfert

1. Introduction

Active Galactic Nuclei (AGN) are believed to be powered by accretion of material onto a supermassive black hole. Intrinsically narrow emission lines from the accretion disk are

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predicted to produce double-horned profiles due to the Doppler effect (unless viewed face-on). Near the innermost stable orbit the gas velocity approaches the speed of light and special relativistic beaming should enhance the "blue" peak on the approaching side relative to that on the receding ("red") side. Gravitational and transverse Doppler effect are expected to redistribute photons to lower energies and introduce asymmetric offsets of the Doppler horns from the rest-energy. The sum of contributions over a range of annuli would then give a broad (FWHM $\Delta E/E \sim 0.3$) asymmetric profile (Laor 1991; Fabian et al. 2000). The X-ray band-pass contains the strongest such line, Fe Kα, emitted via fluorescence or recombination processes between 6 – 7 keV, depending on the ionization-state of the gas. This line is commonly observed in AGN (e.g., Nandra et al. 1997) with both narrow (Yaqoob et al. 2001) and a broad components (e.g., Tanaka et al. 1995); the former may arise in cool material close to the optical broad-line-region while the latter is thought to originate close to the black hole (see Fabian et al. 2000 and references therein). However, there is some controvery as to the origin of the broad line component, with broadening mechanisms such as Comptonization (Misra & Sutaria 1999; Misra & Kembhavi 1998) being suggested, along with other possibilities (e.g., Schurch et al. 2002; Zdziarski et al. 1996).

X-ray detectors prior to *Chandra* had only moderate energy resolution around 6 keV (e.g. $\Delta E/E \sim 0.02$) leaving the detailed line shape and origin unclear. The high-energy-transmission grating spectrometer (HETGS; Markert et al. 1994) of *Chandra* gives a factor ~ 4 improvement in energy resolution at 6 keV compared to detectors flown previously, allowing isolation of contributions to the profile from weak narrow features. The EPIC CCDs on board *XMM-Newton* (hereafter referred to as *XMM*) yield high throughput, allowing tight constraints on the continuum and broad line. Together these satellites offer an unprecedented insight into the Fe Kα profile. Here we present results from overlapping *Chandra* and *XMM* observations of NGC 3516, revealing new features that provide compelling evidence the line is indeed modified by special and general relativistic effects.

2. New *Chandra* and *XMM* Results

A *Chandra* observation of NGC 3516 between 2001 November 11 UT 01:00:25 – November 12 UT 02:19:22 overlapped an *XMM* observation covering November 09 UT 23:12:51 to November 11 UT 10:54:19 and a *RXTE* observation November 11 UT 10:05:36 - 11:10:56 (Figure 1). *Chandra* data were reprocessed using `CALBD v2.6` and `CIAO v2.1`, removing bad pixels, columns, period of high background and events with detector 'grades' *not* equal to 0, 2, 3, 4, or 6 thus yielding an exposure of ~75 ks. The EPIC data reduction pipeline was run with SAS v5.2.0. The EPIC data utilized the thin filter with PN Prime Small Window mode, MOS1 Small Window Free Running mode and MOS2 Large Window mode. These data were screened to remove hot and bad pixels and periods of high background, yielding an exposure of 80 ks (20 ks overlapped *Chandra*). At this flux level the photon pileup is negligible. Instrument patterns (grades) 0 - 12 (MOS) and 0 - 4 (PN) were selected. EPIC spectra were extracted from a cell $\sim 0.94'$ diameter, centered on the source. Background spectra were extracted from a nearby region for the PN ($< 1\%$ of the source count rate) and ignored for the MOS detectors (the small window mode in the MOS leaves no nearby regions for background extractions, but background is negligible at this flux level). *RGS* data will be presented in a later paper. The *RXTE* observation of 3.5 ks overlapped the *XMM* and *Chandra* data as shown (Figure 1).

3. The X-ray Spectrum

We found NGC 3516 to have a flux $F_{2-10keV} \sim 1.3 - 1.5 \times 10^{-11}$erg cm^{-2} s^{-1}, the lowest observed, first exhibited during a *Chandra* LETG observation (Netzer et al. 2002). The mean *XMM* data reveal a complex spectrum, flat in the 2-10 keV regime with evidence for transmission through ionized gas as previously observed in this source (e.g., Netzer et al. 2002; Kraemer et al. 2002; Kriss et al. 1996). The *XMM* light curves and hardness ratio suggested a natural division $\sim$ 60ks into the observation. The second segment of *XMM* data were fit together with the entire *Chandra* dataset during a time-period denoted T2. While not ideal (the *Chandra* data extending beyond the end of the *XMM* observation), this division of the data proves enlightening.

We examined the ratio of Fe Kα photons relative to the local continuum. Figure 2a shows the HETG data alone, for clarity. The positive and negative data from the first order of the HEG are combined with those of the MEG (up to 6.5 keV). The Fe Kα emission is clearly visible with a strong peak at rest-energy 6.41 keV. The associated Fe Kβ line is also seen at 7.06 keV consistent with the expected strength $\sim 11\%$ of the Kα flux. The Fe Kα component has width FWHM $\sim$ 40eV and is constant in flux over the observation. During the latter part of the *XMM* observation (T2) the EPIC PN data hint at a double line peak but the MOS data do not confirm it and the HETG data are ambiguous. The constancy in flux, the width and energy indicate the bulk of the line at 6.4 keV probably arises in cool material located at least several light-days from the nucleus rather than the accretion flow, thus we do not consider this component or the associated Kβ component further.

Most importantly, additional and unexpected lines are evident at 5.57 keV and 6.22 keV. The line widths are consistent with zero, with upper limits $FWHM \sim 500$ and 40 eV, respectively. The line at 5.6 keV is weak and it is difficult to separate it from the broad red wing, hence the extremely loose constraint on width. This fine structure has never before been seen in an AGN and the lines do not correspond to any emission lines expected of appreciable strength. These are not statistical fluctuations, they show up in the positive and negative sides of the dispersed spectra from both parts of the HETGS. Overlapping *XMM* data from T2 (Figure 2b) confirm the existence of a feature at 6.2 keV and show other features between 6.8 – 6.9 keV in the *XMM* data (Figures 2b, c).

Table 1 details line fluxes obtained from the HETGS and two subsets of *XMM* data, revealing variability in the lines at 5.6 and 6.2 keV at > 99% confidence. The "difference spectrum" (Figure 2d) i.e., the spectrum from T2 minus that from T1, further highlights the variable components, confirming changes in the line profile at > 99% confidence. The apparent variability of the 5.6 keV line may be due to a shift of the line peak from 5.4 to 5.6 keV (the *HETG* data is weighted to a later time). Binning the line coarsely illustrates that *Chandra* (Figure 2e) and *XMM* (Figure 2f) data both show a broad component of the same extent, with an equivalent width ~ 800eV (when modelled as a broad Gaussian component). Figure 2f shows the broad component of the line maintains a ~constant equivalent width, while that of the narrow line changes from 216 eV (T1) to 172 eV (T2) as the continuum changes flux.

4. Discussion

We now consider the origin of the newly discovered features. While the line at 6.2 keV matches the energy of the first peak of a Compton shoulder, the observed line is too sharp and strong to be attributed to this. It has been proposed (Skibo 1997) that the destruction (spallation) of Fe into Cr and other lower Z metals on the surface of the accretion disk enhances the line emission expected from elements of low abundance. In this way lines at ~ 5.6 and 6.2 keV from CrXXIII and MnXXIV could be enhanced to a detectable level. The observed Cr to Mn ratio, however, is inconsistent with the spallation model (Skibo 1997), which considers a wide range of physical conditions. The lines are most likely due to Fe, shifted by relativistic effects.

Absorption from an infalling blob of gas was previously suggested to explain the complex and variable profile observed with *ASCA* (Nandra et al. 1999). However our data cannot be explained that way unless the line width is also highly variable, which seems unlikely. If the emission line at 5.6 keV is from infalling neutral gas, the implied velocity must be $> 40,000$ km s^{-1}. However, infalling gas would have to be ionized such that resonance line and bound-free opacity were small enough that the gravitational attraction of the disk/black hole system could overcome radiation pressure (Proga, Stone, & Kallman 2000) (thus flow velocities would be even higher). However, the apparent shifts in the line energy (5.4 – 5.6 keV) with time are more indicative of deceleration of an outflowing blob.

Recently, *Chandra* observations of the Galactic X-ray binary SS 433 revealed relativistically red- and blue-shifted lines from FeXXVI Ly-α (6.966 keV) and FeXXV 1s2p-1s^2 (6.685 keV), with an outflow velocity of $\approx 0.27c$ (Marshall et al. 2002). The narrow lines at 5.6 eV and 6.2 keV observed in NGC 3516 cannot be explained by H- and He-like Fe emission from a single flow. However, if the lines are NiXXVII 1s2p-1s^2 (7.789 keV) and FeXXVI Lyα, the redshifts are consistent with a single velocity, $\sim 0.25c$ (assuming a disk inclination of 38° Wu & Han 2001). In fact, Marshall et al. (2002) report the detection of relativistically red-shifted NiXXVII in SS 433. Wang et al. (2000) predict that blobs of gas originating from disk instabilities will be initially be fully ionized, but will show line emission via recombination sometime after ejection ($\sim$ days, assuming T $\sim 10^8$K, and $n_e \sim 10^{10}$ cm^{-3}). Hence it is possible that these emission lines are recombination lines of He-like Ni and H-like Fe, although the observed flux ratio would require enhancement of Ni due to anomalous abundances or a peculiar ionization balance in the recombining gas. Since there are no blue-shifted features (at 9.19 keV and 8.21 keV) the "jet" must be one-sided, perhaps an example of the MHD driven jets suggested by Chagelishvili, Bodo & Trussoni (1996). As we see the red side, our line-of-sight to the jet, presumably through the inner regions of the accretion disk, cannot be blocked by a Compton-thick layer.

It has been debated (Misra & Sutaria 1999; Fabian et al. 1995; Reynolds & Wilms 2000; Ruszkowski et al. 2002) whether thermal Comptonization of a narrow Fe Kα line could explain the broad components in AGN. The presence of sharp line features means no Comptonizing medium exists between us and the nuclear environs. Thus the broad line in NGC 3516, and probably other AGN, must be produced by general relativistic effects. The alternative suggestion, that the broad feature is an absorbed continuum component, does not allow us to avoid invoking relativistic effects to explain the sharp features.

The constraints on the velocity widths of the new features indicate they originate in material with an organized kinematic structure such as the accretion disk, arising from very narrow annuli or hotspots (Semerak, Karas & Felice 1999; Navakshin & Kazanas 2001). Reverberation of flares across the disk predicts narrow features (Young & Reynolds 2000) but they should only exist for a few hundred seconds. If the gas is ionized, the intrinsic Fe Kα line could be emitted at 7 keV requiring extreme relativistic shifts in the maximally-rotating Kerr metric (Laor 1991), viewed at low inclinations to match observed features. The central regions of NGC 3516 are indicated to be inclined at 38° (Wu & Han 2001). Thus the lines would be produced between 3 - 5 gravitational radii (R_g) where relativistic effects predict lines significantly broader and less "peaky" than observed, assuming we see a full orbit of the material round the black hole. Orbital timescales ($t_{\rm orb} \sim (r/9R_g)^{3/2}M_8$) are 1 – 2.3 hours for 3 – 5 R_g (around black hole mass $M \sim 2.3 \times 10^7 M_\odot$ estimated for NGC 3516; Di Nella et al. 1995). Our spectra sample several orbits of material this close to the black hole. Thus line widths allow us to rule out an origin in an ionized disk around a spinning black hole.

Alternatively, the features arise in cool gas, where the required energy shifts are smaller than in the previous picture. The peak at 5.6 keV could be the red horn of a line from $\sim$ 35 R_g (a weak peak close to 6.9 keV may be the blue horn associated with this). The 6.2 and 6.5 keV peaks could then be the horns of a line from $\sim$ 175 R_g (Figure 4). At these radii the feature widths match predictions for narrow illuminated annuli or orbiting blobs of gas (175 R_g may be outside the disk structure). Emission from a very restricted area on the disk was previously suggested by Iwasawa et al. (1999) based on a flare state for MCG-6-30-15. Thus the phenonenon observed here is probably generally applicable to AGN. The lack of strong features blueward of 6.4 keV is a problem for all the models discussed here. Occultation models (as suggested for MCG-6-30-15; McKernan & Yaqoob 1998) may be applicable, where different regions of the disk become visible at different times.

In summary, new data show spectral features most likely explained as Fe Kα lines, modified by relativistic effects. An increase in the hard X-ray continuum flux is correlated with the detection of these lines. Regions of magnetic reconnection would illuminate very small areas of the accretion flow and may provide the source of enhanced continuum emission. Reconsideration of the *ASCA* data in light of the new *Chandra* results indicates that the phenomenon driving the variations in line profile has been going on for at least several years and over a range of nuclear luminosity.

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Table 1. HETG Narrow Components of Fe Kα

Energy (keV)	$\mathrm{Flux}_{\mathrm{T1-XMM}}$	$\mathrm{Flux}_{\mathrm{T2-XMM}}$	$\mathrm{Flux}_{\mathrm{HETG}}$
5.57 ± 0.02	$0.00(< 0.53)$	$0.00(< 2.89)$	$7.37(5.90 - 8.60)$
6.22 ± 0.04	$6.26(5.07 - 7.94)$	$9.90(5.92 - 13.3)$	$11.1(9.45 - 13.0)$
6.41 ± 0.01	$36.5(34.8 - 38.5)$	$33.5(28.7 - 37.7)$	$31.7(26.9 - 34.1)$
6.53 ± 0.04	$8.19(6.94 - 10.2)$	$8.98(4.67 - 12.6)$	$7.43(5.47 - 9.95)$
$6.84 - 6.97$	$5.12(2.75 - 5.99)$	$5.78(0.97 - 8.18)$	...

[a]Errors are $\chi^2 + 2.71$ with line energies fixed and assumed narrow (except for that at 6.4 keV where the fitted width was fixed). Line fluxes in units $\times 10^{-6}$ photons cm^{-2} s^{-1}. We tabulate fluxes for lines appearing at 6.84 ± 0.01 (T1) and 6.97 ± 0.06 keV (T2) in *XMM* data. A simple broad Gaussian component was included in the fit to parameterize the broad line.

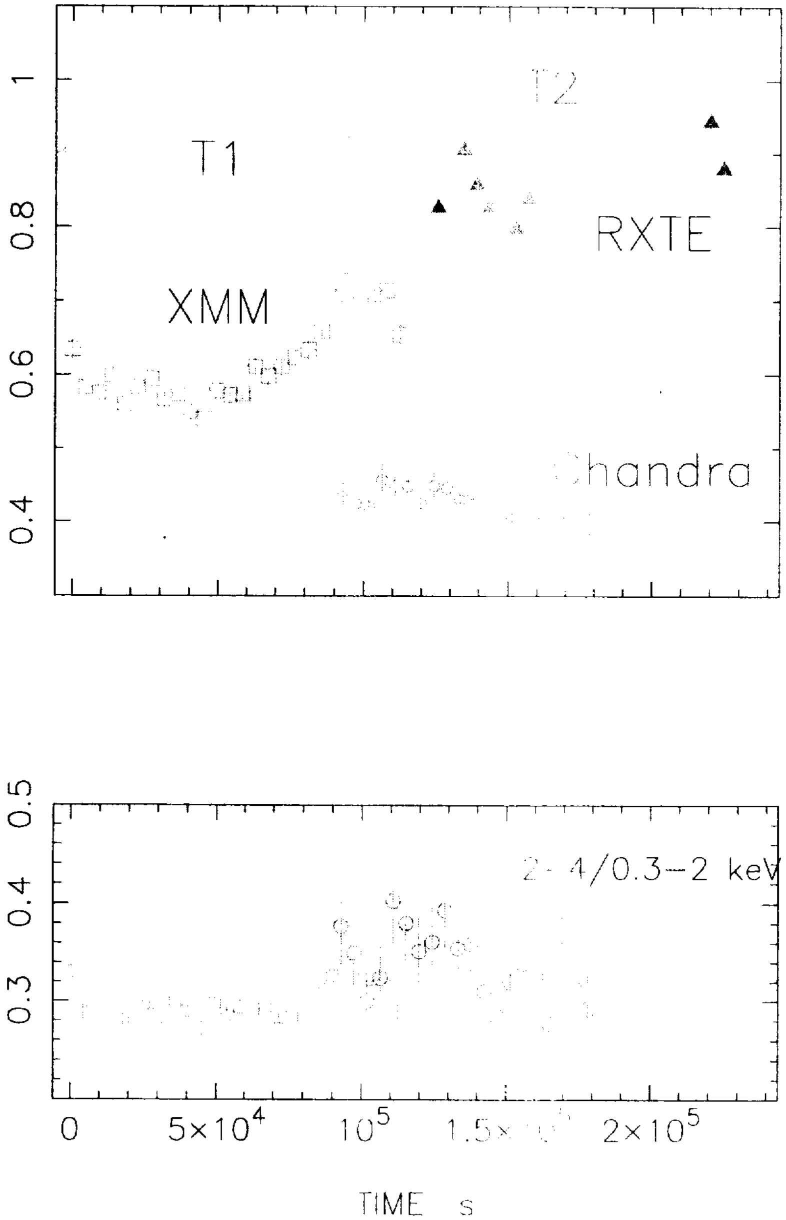

Fig. 1.— The upper panel shows light curves from *XMM* (2-6 keV, green squares); *Chandra* (2-6 keV, magenta circles) and *RXTE* (3-30 keV, red triangles). The time is shown in seconds relative to the start of the *XMM* observation at 2001 November 09 UT 23:12:51. The *Chandra* data have been scaled up by a factor 4, the *RXTE* data have been scaled down by a factor 12.5, for clarity of display. The lower panel shows the hardness ratio, 2-4/0.3-2 keV, based on the *XMM* PN data and *Chandra* ACIS data. The series are in 4500 s time bins and the *Chandra* ratio has been scaled down by a factor of 4, for display.

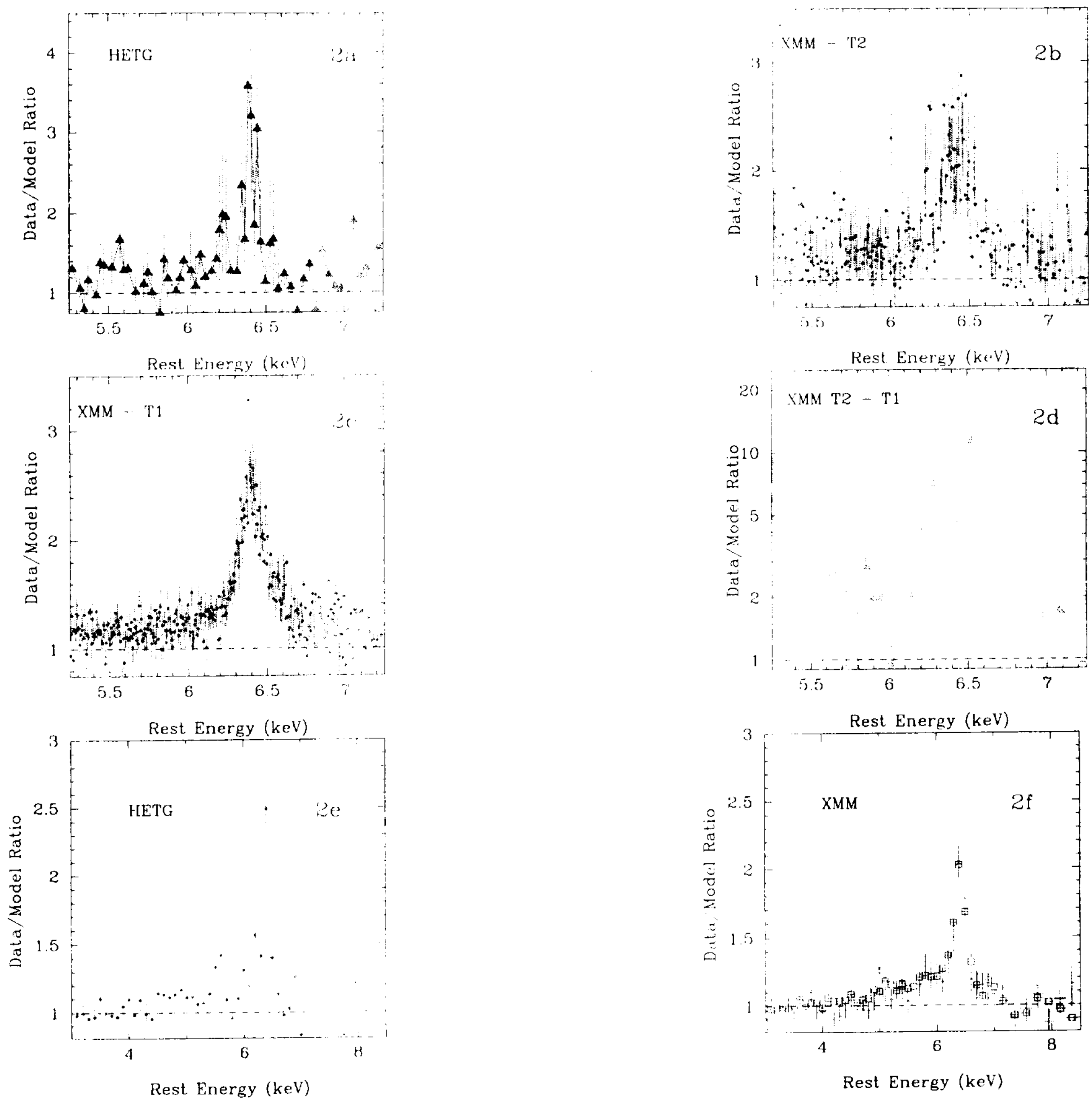

Fig. 2.— The X-ray data/continuum model ratios in the Fe Kα regime. Data from the high-state with *HETG* (a) and *XMM* (b). HETG data are the sum of the positive and negative 1st order grating spectra plus MEG data up to 6.5 keV. Also *XMM* data from the low-state (c) and the difference spectrum (the high-state minus the renormalized low-state spectra for PN, MOS1 and MOS2) compared to a power-law fit (d: *XMM* data alone). e) shows the coarsely-binned HETG data; (f) the *XMM* data (T2 - blue squares, T1 - green crosses); we combine data from PN, MOS1 and MOS2, which agree when viewed individually.

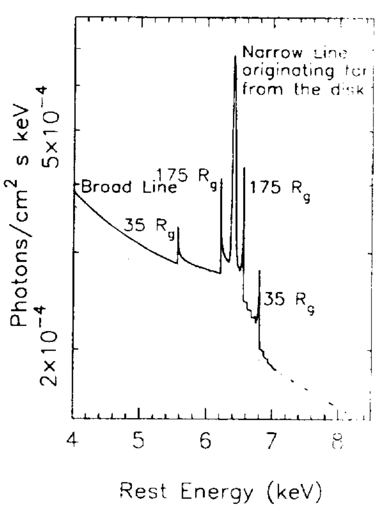

Fig. 3.— A schematic representation of the components of the Fe Kα line in NGC 3516. The green line shows the continuum level.

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