THE PROPERTIES OF THE RELATIVISTIC IRON K-LINE IN 
NGC 3516

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ABSTRACT

We present an analysis of the relativistic iron Kα line in the Seyfert 1 galaxy NGC 3516, based on a continuous, five-day ASCA observation. The broad profile which has been found in several other AGN is confirmed in NGC 3516 with unprecedented signal-to-noise ratio. Disk-line models with either a Kerr or Schwarzschild metric fit the integrated profile, but both require emission very strongly concentrated in the inner disk. We find tentative evidence for the line signatures of Ni Kα and/or Fe Kβ. The continuum flux varied by ~ 50 per cent during the observation and time-resolved analysis shows that the line also changes. The line core seems to follow the continuum, but the blue wing is unrelated and shows a greater amplitude (factor ~ 2) of variability. The red wing is formally consistent with a constant but appears to be correlated with the blue wing. We interpret this as evidence for independent variability of the broadest parts of the line. There also appears to be an absorption feature in the profile, consistent with resonance scattering in infalling material. This variable feature may be the signature of material being accreted by the central black hole.

Subject headings: galaxies:active – galaxies: nuclei – X-rays: galaxies – galaxies: individual (NGC 3516)

1. INTRODUCTION

A long ASCA exposure of the Seyfert 1 galaxy MCG-6-30-15 revealed a broad, redshifted profile to the iron Kα line (Tanaka et al. 1995). The line is thought to arise from

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the inner regions of an accretion disk close to the central black hole, the profile being the result of extreme Doppler and gravitational shifts (e.g., Fabian et al. 1995). “Snapshot” observations of other Seyferts have shown these broad lines to be common and defined the mean properties (Nandra et al. 1997b, hereafter N97b; Reynolds 1997). Furthermore, Iwasawa et al. (1996, hereafter I96) have presented evidence that the profile of MCG-6-30-15 is variable, being extremely broad and redshifted in the “deep minimum” state (see also Reynolds & Begelman 1997; Young, Ross & Fabian 1998; Iwasawa et al. 1999).

It is of great interest that the line profile is observed to vary in this way, and indeed at all. The lines typically arise around $20R_g$ (Tanaka et al. 1995; N97b) and should therefore be highly responsive to continuum variations: the expected lag due to reverberation is of order $\sim 1000s$. In the time taken to accumulate a typical ASCA spectrum ($\sim 20 - 40$ ks) we would therefore expect the line profile to relax to its mean state and appear similar at all times. I96 suggested that, rather than due to reverberation, the profile changes might be due to a changing pattern of illumination of the disk (see also Weaver & Yaqoob 1998; McKernan & Yaqoob 1999; Reynolds et al. 1999). Here we report on a long observation of the Seyfert 1 galaxy NGC 3516 ($z=0.009$), which is known to be variable and have a broad, redshifted iron Kα line (Kriss et al. 1996; N97 a,b,c), offering the opportunity for performing analysis similar to that of MCG-6-30-15.

2. OBSERVATIONS

The ASCA observation began on 1998-Apr-12 at 21:44:50 and lasted for $\sim 4.5$ days. We used data from both Solid–state Imaging Spectrometers (SIS0/SIS1), and the two Gas Imaging Spectrometers (GIS2/GIS3). The SIS data were collected in 1-CCD readout mode using FAINT telemetry mode. The data were analyzed according to the methods described in Nandra et al. (1997a,b) and references therein. The total exposure times after screening were 152 ks for the SIS detectors and 186 ks for the GIS, making this one of the longer ASCA exposures of a single object. The mean count rates for the observation were $0.978 \pm 0.003$, $0.806 \pm 0.002$, $0.587 \pm 0.002$ and $0.724 \pm 0.002$ for SIS0, SIS1, GIS2 and GIS3 (SIS: 0.5-10 keV; GIS: 1-10 keV). The average 2-10 keV flux, determined using a power-law model, was $4.7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which lies between the flux states described by N97c.
3. MEAN LINE PROPERTIES

We first analyzed the integrated spectrum. The X-ray spectrum of NGC 3516 is absorbed by a column of partially ionized gas (e.g., Kriss et al. 1996) and we restricted our initial analysis to the 3-10 keV band to minimize its effects. We found no evidence for an iron K-edge from the ionized gas. Fig. 1 shows the line profile of NGC 3516 derived from the SIS data only, derived by adopting a local power law fit in the 3-4 and 7-10 keV range to the SIS+GIS data. It is clearly broad and red-shifted, and shows a very similar shape to MCG-6-30-15 (Tanaka et al. 1995), the mean for Seyfert 1 galaxies (N97b) and previous observations of NGC 3516 (N97c). The profile can be modeled adequately with two gaussians, a narrow “core” and broad, redshifted “wing”, with parameters detailed in Table 1. The fit gave a rather flat photon index compared with previous ASCA observations (N97c), with $\Gamma = 1.56 \pm 0.04$ and an acceptable $\chi^2$ of 1703.0/1736 d.o.f.

We next fitted the data with the Schwarzschild disk line model of Fabian et al. (1989). Such disk line models are rather complex, with considerable degeneracy which makes the $\chi^2$-fitting process susceptible to traps in local minima. The solutions we show in Table 1 are the best we have found after searching parameter space extensively. Determination of accurate error bars in these circumstances is severely complicated by the model degeneracies, however, and these should be treated with caution. Fits to the Schwarzschild model provided an excellent fit to the data ($\chi^2=1696.7/1736$ d.o.f) - improving on the double-gaussian model by $\Delta \chi^2=6.3$ for the same number of free parameters. Both the energy of the line and the inner radius pegged at their minimum values (6.34 keV and 6.0 $R_g = R_{\text{ms}}$) in this fit. To improve the stability of the fitting, the inner radius was therefore fixed at $R_{\text{ms}}$ when the parameters in Table 1 were determined. This low inner radius and the extraordinarily steep emissivity index of $q = 8.0$ indicate that the line emission is very strongly concentrated in the central regions, where the most extreme relativistic effects operate. Another way of enhancing these relativistic effects is to allow the disk to extend closer to the black hole, which is possible when the hole is rotating. Fits to the Kerr model of Laor (1991) are also given in Table 1. In this case the outer radius cannot be constrained and was fixed at the maximum value allowed by the implementation of the model (400$R_g$). The $\chi^2$of 1703.4/1736 dof for is slightly worse than the Schwarzschild case but the parameters, in particular the emissivity law, are more in line with our prejudices about the source geometry. For a disk centrally-illuminated by a point source we expect $q \sim 0 - 3$, for example. The Kerr model is plotted as the dotted line in Fig. 1.

Weaker lines from iron K$\beta$ and Ni K$\alpha$ are also expected from the accretion disk (e.g., George & Fabian 1991), and indeed Fig. 1 shows some evidence for excess flux around the expected energies of 7-7.5 keV. We have added additional disk lines to the Kerr and
Table 1. Line parameters derived from fitting the mean spectrum.

<table>
<thead>
<tr>
<th></th>
<th>Core</th>
<th>Wing</th>
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<tbody>
<tr>
<td>Double gaussian:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>1.56 ± 0.04</td>
<td>...</td>
</tr>
<tr>
<td>$E_{K\alpha}$</td>
<td>6.31 $^{+0.04}_{-0.04}$</td>
<td>5.36 $^{+0.24}_{-0.40}$</td>
</tr>
<tr>
<td>$\sigma_{K\alpha}$</td>
<td>0.09 $^{+0.07}_{-0.09}$</td>
<td>1.16 $^{+0.45}_{-0.29}$</td>
</tr>
<tr>
<td>$I_{K\alpha}$</td>
<td>0.74 $^{+0.18}_{-0.16}$</td>
<td>2.78 $^{+1.82}_{-0.95}$</td>
</tr>
<tr>
<td>$W_{K\alpha}$</td>
<td>140 $^{+34}_{-30}$</td>
<td>470 $^{+310}_{-160}$</td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td>1703.0/1736</td>
<td>...</td>
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<thead>
<tr>
<th>Disk line:</th>
<th>Schwarzschild</th>
<th>Kerr</th>
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<tbody>
<tr>
<td>$\Gamma$</td>
<td>1.53 $^{+0.03}_{-0.04}$</td>
<td>1.52 $^{+0.05}_{-0.02}$</td>
</tr>
<tr>
<td>$E_{dl}$</td>
<td>6.40 $^{+0.07}_{-0.00}$</td>
<td>6.54 $^{+0.05}_{-0.09}$</td>
</tr>
<tr>
<td>$q$</td>
<td>8.0 $^{+2.0}_{-3.3}$</td>
<td>2.71 $^{+0.12}_{-0.15}$</td>
</tr>
<tr>
<td>$R_i$</td>
<td>6.0 (F)</td>
<td>2.8 $^{+1.0}_{-1.6}$</td>
</tr>
<tr>
<td>$R_o$</td>
<td>80 $^{+\infty}_{-71}$</td>
<td>400 (F)</td>
</tr>
<tr>
<td>$i$</td>
<td>35 $^{+1}_{-2}$</td>
<td>0 $^{+19}_{-0}$</td>
</tr>
<tr>
<td>$I_{dl}$</td>
<td>2.8 $^{+0.2}_{-0.2}$</td>
<td>2.4 $^{+0.4}_{-0.4}$</td>
</tr>
<tr>
<td>$W_{dl}$</td>
<td>620 $^{+40}_{-40}$</td>
<td>530 $^{+80}_{-80}$</td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td>1696.7/1736</td>
<td>1703.4/1736</td>
</tr>
</tbody>
</table>

Note. — $\Gamma$ is the continuum photon index; $E_{K\alpha}$ is the centroid energy of the gaussian in keV; $\sigma_{K\alpha}$ is the width (keV); $I_{K\alpha}$ is the intensity of the gaussian in units of $10^{-4}$ ph cm$^{-2}$ s$^{-1}$; $W_{K\alpha}$ is the equivalent width in eV; $E_{dl}$ is the rest energy of the disk line (keV); $q$ is the emissivity index (see text); $R_i$ is the disk inner radius; $R_o$ is the disk outer radius; $i$ is the disk inclination; $I_{dl}$ is the intensity of the disk line ($10^{-4}$ ph cm$^{-2}$ s$^{-1}$); $W_{dl}$ is the equivalent width of the disk line (eV); (F) denotes that the parameter has been fixed; P denotes that the parameter “pegged” at a limiting value.
Schwarzschild models to represent emission from Fe K$\beta$ and Ni K$\alpha$. The energies were fixed at the neutral values of 7.06 keV and 7.47 keV (rest frame) respectively, the fluxes were left free, but all other disk line parameters were tied to those of Fe K$\alpha$. For the Kerr model, we find a decrease in fit-statistic of only $\Delta \chi^2=2.2$ for Fe K$\beta$, but a significant improvement ($\Delta \chi^2=5.5$) for Ni K$\alpha$. The EW of these lines are unconstrained, but the best-fit values are 60 eV and 80 eV respectively (c.f. 560 eV for Fe K$\alpha$). For the Schwarzschild model both lines are highly significant, with K$\beta$ having $\Delta \chi^2=6.3$ and Ni K$\alpha$ $\Delta \chi^2=14.1$, and EW=100 eV and 150 eV. Using an optimistic error prescription of $\Delta \chi^2=2.3$ we constrain the ratio of Fe K$\beta$/Fe K$\alpha= 0.14 \pm 0.09$, consistent with the theoretical expectation for neutral iron of 0.11 (Kikoin 1976). The Ni K$\alpha$/Fe K$\alpha$ ratio is $0.19 \pm 0.07$, a little higher than than the $\sim 0.07$ expected based on the fluorescence yields, and solar abundances.

Although the disk line clearly accounts for the bulk of the flux and provides a good fit, it is possible that there is a contribution from more distant material, such as the BLR or molecular torus (e.g. Ghisselini, Haardt & Matt 1993; Krolik, Madau & Zycki 1993). Indeed adding a narrow line with fixed energy at 6.4 keV does improve the fit in both cases with $\chi^2=1684.0/1735$ dof for the Schwarzschild model ($\Delta \chi^2=12.7$; equivalent width, EW= $50^{+30}_{-10}$ eV) and $\chi^2=1682.8/1735$ dof for the Kerr ($\Delta \chi^2=20.6$; EW=90$^{+60}_{-50}$). Aside from a reduction in the flux (and EW) the disk line parameters remain consistent within the errors. This model is shown as the dashed line in Fig. 1. Another interesting possibility is that there is an absorption component present in the red part of the line. Adding such an absorption line to the Schwarzschild model gives $\chi^2=1690.2/1734$ dof ($\Delta \chi^2=6.5$). For the Kerr model we obtain $\chi^2=1675.1/1734$ dof ($\Delta \chi^2=28.3$) for a narrow absorption line and a further improvement to $\chi^2=1670.4/1733$ when the absorption line is slightly broadened ($\sigma=0.2$ keV). This last model is the best of all attempted against the integrated profile and is shown as the bold line in Fig. 1. Further evidence for the absorption feature is afforded by the time-resolved profiles, which we explore next.

4. LINE VARIABILITY

The continuum of NGC 3516 varied by a factor of $\sim 50$ per cent during the observation (Fig. 2), and we have searched for variations in the emission line too. We split the dataset into 8 segments, designated P1-P8, with equal durations (46.4 ks). These are marked on the light curve in Fig. 2. These segments have a typical exposure of $\sim 20$ ks, which is just sufficient for meaningful determination of the line parameters. We used the same, standard binning for all spectra. The bins in each spectrum satisfy our usual criterion of $> 20$ ct/bin, but the standard binning method ensures that when comparing line profiles, no spurious
differences appear due to different binnings. We employed several different methods of modeling the continuum to deconvolve the line: a) a power law fit in the 3-4 and 7-10 keV bands (as above), b) a two-gaussian fit to the 3-10 keV data, with energies and widths fixed at those for the mean profile then the gaussians removed, and c) a photoionization fit to the full band data, excluding the 4-7 keV band. In practice these all gave similar results. We show the data/model ratios derived from a) in Fig. 3. The peak seems to occur close 6.4 keV (shown by the vertical, dotted line) in most cases. Although individual profiles are noisy there does appear to be some variation in the shape of the line.

We have quantified the profile variations by dividing the line into three parts resolved in energy: the “red wing” (4-6 keV), “core” (6.0-6.4 keV) and “blue wing” (6.4-6.8 keV). We took the data model ratios in these bins and converted them into line fluxes using the fitted continuum. The resulting light curves are shown in Fig. 2. $\chi^2$-tests against a constant show variability at $\sim$ 80, 95 and 99 per cent confidences for the red wing, core and blue wing. The red and blue wing fluxes appear uncorrelated with the continuum variations. A strictly proportional relationship between the blue wing and continuum is ruled out at $\sim$ 99 per cent confidence, based on a $\chi^2$ test. Interestingly, however, the wings appear to be correlated with each other. A linear (Pearson) correlation shows a coefficient of $r = 0.69$, significant at $\sim$ 95 per cent confidence. The core is evidently variable with a poor $\chi^2$ of 13.1 for a constant intensity. Assuming a 1:1 linear relationship with the continuum gives a much better, and acceptable $\chi^2$ of 10.0/8 d.o.f. despite having 1 fewer degree of freedom. This offers some evidence that the continuum and line core are correlated and vary in strict proportion, although the Pearson coefficient of $r = 0.49$ is not significant in this case. We also fitted disk line models to these individual spectra, but were not able to identify a single parameter which accounts for the changes in profile.

Notwithstanding the complexity in determining the emission properties, the absorption feature at 5.9 keV found in the mean spectrum does appear to be variable. We have fitted the SIS spectra only, which are much more sensitive to the feature, with the “template” Kerr model from the mean spectrum. The continuum spectral index and line flux were allowed to vary, but all other line parameters were fixed at the mean. We then added an absorption line at 5.89 keV, derived from the mean spectrum, to the model. We found significant features (at $> 99.5$ and $> 95$ per cent confidence) in the P4 and P5 spectra ($\Delta \chi^2 = 9.6$ and $\Delta \chi^2 = 4.7$: see inset to Fig. 1), but insignificant improvements ($\Delta \chi^2 < 2.2$) in all other spectra. Examining the line profiles one could speculate that the feature was present in some of the other spectra, but at different energies. For example, P1 gives $\Delta \chi^2 = 6.0$ for a feature at 5.8 keV, significant at 95 per cent confidence. At this stage it is unclear whether the feature is variable in strength, energy or both. A possible alternative explanation for the shape of the P4/P5 line is that we are seeing two separate components,
a core around 6.4 keV and a strongly-redshifted and broad component at $\sim 5.5$ keV. The latter is reminiscent of the profile occasionally seen in MCG-6-30-15 (I96). The absorption interpretation seems preferable, however, as an examination of, e.g., the P2 and P7 profiles is more suggestive of a single line.

5. DISCUSSION

We have presented a broad, iron-line profile of NGC 3516 with unprecedented signal-to-noise ratio. Disk models give an excellent fit to the data, and indicate a strong concentration of the emission in the close to the central black hole. We cannot distinguish between rotating and non-rotating black hole models using these data alone, although the disk-line parameters seem more plausible for a Kerr geometry. There is also some evidence in the mean profile for a narrower component which arises from somewhere other than the inner accretion disk, and/or an absorption feature at around 5.9 keV. There is also tentative evidence for the Fe K\text{\textbeta} and/or Ni K\alpha lines in the integrated spectrum. Consideration of the line variability suggests that the profile is variable, meaning that the fits to the integrated spectrum offer only a partial picture of the central regions. The profile changes are not easily interpretable, but energy-resolved light curves indicate that the core of the line responds to the continuum, but that the extended wings do not. These fluxes are also variable, however, and are correlated with each other. The clearest interpretation of this is that the red and blue wings form a single, broad component with a common origin in the inner disk, but that a large fraction of the core comes from somewhat larger radii.

The profile changes may be considered surprising given the relatively weak continuum variability, and the inference that the bulk of the flux in the line probably arises from within 100 $R_g$ (Tanaka et al. 1995; N97b). The light-travel time is only 5000 $R_{100}M_7$ s (where $R_{100}$ is the radius in units of 100 $R_g$ and $M_7$ the mass in units of $10^7$ M$_\odot$, which we consider a reasonable estimate; see, e.g., Edelson & Nandra 1999). The line should therefore respond fully to any continuum changes in the integrations presented in Fig. 3 and they should simply exhibit the mean profile. If due to reverberation, the profile variations would imply that we have seriously underestimated either the size of the emission regions (e.g. Hua, Kazanas & Cui 1999) and/or the black hole mass. Also, the variation of the “blue wing” is in excess of a factor 2, which is more than the continuum (Fig. 2). Reverberation cannot produce such an over-response without changes in ionization state, for which we have no evidence. More likely the profile variations are dominated not by reverberation, but some other process which acts in a different manner or on a longer time scale. For example the variation in the blue wing could be due to an enhancement in the illuminating
flux of the inner disk portion moving towards us, due to a local flare (c.f. I96, Iwasawa et al. 1999). Strong gravitational effects in transverse or receding portions at the same radius would account for the correlation between the red wing and blue core. A more “standard” reverberation picture may be relevant for the core, which comes from further out where the X-ray source appears point-like. The apparent response of the core to the continuum on time scales of $\sim 50 \text{ ks}$ still places that flux within $\sim 1000 R_g$, however.

Another physical process which can produce variations in the line profile which are not necessarily related to flux and which can occur on a longer time scale is absorption. Complete absorption (i.e. occultation) has already been suggested as a possible mechanism for profile variability (Weaver & Yaqoob 1998). We interpret our absorption feature at $\sim 5.9 \text{ keV}$, which is evident in the mean spectrum but particularly strong in the P4 and P5 data, as being due to resonance scattering by iron. Resonance absorption features are expected, but unless there is a large velocity gradient in the absorbing material they would typically not be observable in the ASCA spectra as they would be very narrow and therefore weak. As the feature is redshifted with respect to the rest energy of iron K$\alpha$ emission (6.4-6.9 keV), we speculate that the material is infalling and/or suffering gravitational redshift close to the central hole. Evidence for infalling material in AGN is relatively scarce and, if confirmed, such resonance absorption features could provide rare, hard evidence for material actually accreting onto the black hole. Differential (i.e. tidal) changes in the gravitational field would naturally provide a large, apparent velocity gradient in the material, broadening and strengthening the resonance features. Further support for an origin close to the central hole is provided by the variability of the feature, which will be particularly interesting to follow up with the high-resolution XRS calorimeter aboard ASTRO-E.

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Fig. 1.— SIS line profile for the whole observation, created by interpolating a local power-law continuum into the 4-7 keV region. The solid line shows our best fit model for this profile, that of an accretion disk around a rotating (Kerr) black hole, with an absorption line - presumably also due to iron but redshifted - in the low-energy wing of the line. This provides a better fit to the data than a line from the disk line alone (dotted line), even when an additional narrow component is allowed (dashed line). Inset shows the line profile from the parts of the observation (designated “P4” and “P5”: see text and Fig 2) where this absorption feature was found to be the strongest. The arrow marks its location.
Fig. 2.— (Top panel) SIS0/1 mean light curve in the 0.5-10 keV band, with a bin size of 512s. Variations of up to ∼50 per cent are observed. The vertical lines mark the periods which were used for time-resolved spectroscopy (P1-P8). The remaining panels show the results derived from these spectra. In descending order they are the 2-10 keV continuum, and the excess flux above the continuum in three line bands. For the line fluxes, the \( \chi^2 \) values against a constant hypothesis are 9.6, 13.1 and 18.4 respectively, for 7 degrees of freedom in each case. Neither the core nor the wing flux is therefore consistent with a constant and though the red wing is formally consistent with no variability, it appears strongly correlated (at 95% confidence) with the blue wing.
Fig. 3.— SIS data/model ratios for the individual segments marked in Fig. 2, derived from a power law fit the SIS+GIS spectra in the 3-10 keV band. The 4-7 keV data were ignored in this fit then the SIS data returned to derive the profile. There are apparent changes in the profile, but these are not easy to categorize from an examination of this plot.