VARIABILITY OF THE IRON K-EMISSION LINE IN THE SEYFERT 1 GALAXY NGC 3516

K. Nandra1,2 R.F. Mushotzky1, T. Yaqoob1,3, I.M. George1,3, T.J. Turner1,3
1Laboratory for High Energy Astrophysics, Code 660, NASA/Goddard Space Flight Center, Greenbelt, MD 20771
2NAS/NRC Research Associate
3Universities Space Research Association


ABSTRACT

We present strong evidence for variability of the flux of the iron Kα emission line in the Seyfert 1 galaxy, NGC 3516. Two ASCA observations, separated by ~ 1 yr, showed a marked decrease in continuum flux by ~ 60 per cent. The flux in the broad, iron Kα line decreased by the same factor in this time period, with no evidence for changes in the line profile. The line variability is significant at > 99 per cent confidence and rules out models in which the line is produced in a molecular torus located at > 1 pc from the nucleus. An accretion disk is considerably more likely.

Key words: galaxies:active – galaxies: nuclei – X-rays: galaxies – galaxies: individual (NGC 3516)

1 INTRODUCTION

Recent ASCA observations have shown that the iron lines commonly observed in Seyfert 1 galaxies (Nandra & Pounds 1994) are extremely broad, with FWHM of order 50,000 km s⁻¹ (Mushotzky et al. 1995; Tanaka et al. 1995; Yaqoob et al. 1995; Nandra et al. 1996b, hereafter N96). These observations alone provide strong evidence for a black hole/accretion disk system, the line widths being extremely difficult to account for in any other geometry (Fabian et al. 1995). A specific prediction of the disk-line model is that the line should respond rapidly to changes in the continuum, as it is excited by fluorescence in a region close to the central black hole. Evidence for such line variability in Seyfert 1 galaxies has proved surprisingly elusive. The well-studied case of the bright Seyfert galaxy NGC 4151 failed to provide conclusive evidence, despite over 10 years worth of high-quality data (e.g., Warwick et al. 1989). The best cases reported to date have been those of MCG-6-30-15 and NGC 7314, for which Iwasawa et al. (1996) and Yaqoob et al. (1996) have shown changes in the iron Kα profile. Interestingly, in the former case, the variations were such that the narrow and broad components of the line were anticorrelated, meaning that the evidence for variability of the total flux of the line was weak. This is contrary to the predictions of simple accretion disk models, where the line should track the continuum variations in a linear fashion, even on short time scales. Thus it is clearly essential to examine the variations in other sources, to investigate whether or not such behaviour is common.

Here we present two ASCA observations of the bright Seyfert 1 galaxy NGC 3516, separated by a 1 year baseline. This source has shown strong continuum variability in the past, allowing us to search for the associated variations expected in the emission line.

2 OBSERVATIONS

NGC 3516 was observed by ASCA (Tanaka, Inoue & Holt 1994) on 1994-Apr-02 (hereafter observation 1) and 1995-March-12 (hereafter observation 2) using 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. (1996a) and N96. The reader is referred to references within those papers for further details regarding ASCA analysis.

Source events were extracted for all four detectors using a circular cell, centred on NGC 3516, with typical radii
3-4 arcmin. The background was estimated using source-free regions. The total exposure times after screening were of order 30ks for observation 1 and 40 ks for observation 2. Examination of the total count rates for the two observations immediately suggests flux variability. Using similar extraction cells, we obtained $2.50 \pm 0.01 \text{ ct s}^{-1} (0.4-10 \text{ keV})$ in SIS0 for observation 1 and $1.52 \pm 0.01 \text{ ct s}^{-1}$ for observation 2, in the same instrument. We proceeded immediately to analysis of the spectra.

3 LINE PROPERTIES

The X-ray spectrum of NGC 3516 is absorbed by a column of partially ionized gas (e.g., Kriss et al. 1996). However, this warm absorber has a negligible effect on the spectrum above $\sim 3$ keV in observation 1 (George et al. 1996). We have verified that this is also the case for observation 2 and to explore the properties of the line have used only the data in the 3-10 keV band.

As shown by N96, NGC 3516 exhibits a line profile typical of Seyfert 1 galaxies, which is characteristic of an accretion disk orbiting a central black hole (e.g., Fabian et al. 1989). We show in Fig. 1 the line profiles determined from the two observations by fitting a power-law model to the SIS data in the 3-5 and 7-10 keV ranges, i.e. excluding the “iron band”. Several things are apparent from this figure. First, the iron Kα line is very broad and asymmetric in this object, as has already been shown by N96. Furthermore, the profiles determined for the two observations are similar. Most interestingly from the point-of-view of the present paper, however, is the clear change in line flux, particularly evident in the core (6.1-6.7 keV). To quantify this further and estimate the statistical significance of this change in line flux, we have employed the disk-line model of Fabian et al. (1989) in addition to the power law in the 3-10 keV band. Such a model provides an excellent fit to both datasets. However, there are too many free parameters in that model to provide a clear indication of the line variability. We therefore made the assumption, justified by Fig. 1, that the line profile remained constant between the two observations, and adopted the disk-line parameters determined by N96 to define that profile. These are a rest energy of 6.4 keV, an inner radius of 6 $R_g$ (where $R_g$ is the gravitational radius of the black hole), an outer radius of 1000 $R_g$, a disk inclination of 27° and an emissivity profile varying as $R^{-q}$ with $q = 2.7$. These parameters are fairly typical for Seyfert galaxies in general. We then fitted the 3-10 keV spectra allowing the power-law parameters and the normalization of the emission line to vary.

The confidence contours obtained from those fits are shown in Fig. 2. This clearly shows that, while the continuum slope is consistent between the two observations, the line flux varied significantly. The 90 per cent confidence regions for the line do not overlap, indicating variability of the line at $> 99$ per cent confidence. The spectral indices are $\Gamma = 1.80^{+0.03}_{-0.02}$ for observation 1 and $1.76^{+0.03}_{-0.03}$ for observation 2 (68 per cent confidence for two interesting parameters). The line fluxes are $2.5^{+0.3}_{-0.3}$ and $1.5^{+0.2}_{-0.3}$, both in units of $10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1}$. The equivalent widths are remarkably consistent at 330$^{+40}_{-40}$ eV and 320$^{+40}_{-40}$ eV respectively. This suggests that the line varied in strict proportion with the continuum. The continuum flux reduced by a factor 1.7 between the two observations and the line flux by a factor $1.7 \pm 0.4$.

If the line arises by X-ray illumination of an accretion disk, we expect it to be accompanied by a “reflection” component due to Compton scattering in the disk (e.g., George & Fabian 1991; Matt et al. 1991). The presence of such a component does not affect our conclusions regarding the line variability. Including a reflection component appropriate for a disk inclined at 27 deg, with a covering fraction of 2$\pi$ reduces both line fluxes by $\sim 20$ per cent to 2.1 $\pm$ 0.3 and 1.2 $\pm$ 0.2 $10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1}$ respectively. Clearly the change is still highly significant. Note, however, that the best-fit power-law index is steeper, with $\Gamma \sim 1.9$, when reflection is included. These effects have already been noted by N96.

Finally, we have investigated whether small variations in the line shape affect our results. Although no large changes are evident in Fig. 1, we have allowed for this by allowing $q$ to be free in the fit to each dataset. Fig. 3 shows the change in the confidence surfaces when we allow the line profile to vary. Clearly the parameter values are not as

![Figure 1. Combined SIS0/SIS1 line profiles for the two observations, which have been created by interpolating a power law continuum excluding the 5-7 keV region. The solid squares represent the data for observation 1, the open triangles those for observation 2. The line flux changes between the two observations, but there is no obvious, or statistically significant, change in profile.](image)
strongly constrained as when $q$ was fixed, however, we still conclude that the line is variable.

4 DISCUSSION

We have presented evidence for variability of the iron Kα emission line in NGC 3516. The line flux changes proportionately with the continuum over a $\sim 1$ yr baseline. This sets a firm upper limit of 1 lt-yr ($R_{\text{max}} \sim 10^{18}$ cm) for the extent of the line-producing region. It is likely to be much smaller than this; the duration of the individual observations is $\sim 1$ d and if the fluorescing material extended over a region much larger than this, the fact that the line changes by the same factor as the continuum would have to be considered as co-incidental, as it would be responding to the continuum averaged over the previous $R_{\text{max}}/c$.

As NGC 3516 shows strong short time scale (i.e. intra-day) variability (Kolman et al. 1993; Nandra et al. 1996a), we therefore conclude that the line is most likely produced in a region $< 1$ lt day in extent. This agrees very well with the predictions of accretion disk models, which are required to explain the broad, asymmetric profiles (Tanaka et al. 1995; N96). Assuming for the moment that $R_{\text{max}} < 1$ lt day), this corresponds to a distance of $\sim 200/M_8 R_g$ gravitational radii, where $M_8$ is the black hole mass in units of $10^8 M_\odot$.

The average line properties for Seyfert 1 galaxies suggest that around 80 per cent of the line emission arises within $\sim 100 R_g$ of the nucleus.

The fact that the Kα line is consistent with a linear change with flux suggests that it originates predominantly from one region. Indeed, the clear change in the core is strongly indicative that this flux comes from close to the central engine. An alternative hypothesis, that the broad component arises from an accretion disk but that the line core is produced in a molecular torus, located far from the nucleus (Ghisellini, Haardt & Matt 1994; Krolik, Madau & Zycki 1994) is strongly disfavored. We conclude that the bulk of the iron Kα emission in NGC 3516, and most likely in the majority of Seyfert 1 galaxies, arises in an accretion disk extremely close to the central black hole.

It is interesting to compare our results with those presented for MCG-6-30-15 by Iwasawa et al. (1996). In that source, while the narrow core of the line was found to be well correlated with the continuum variations, the broad wing was anti correlated, at least on medium time scales ($\sim 1$ day). This is somewhat contrary to the behaviour expected in simple accretion disk models, and may require the invocation of relativistic effects within the X-ray source itself and/or changes in the pattern of X-ray illumination, as well as the light bending and gravitational effects characteristic of a Kerr black hole. On the other hand NGC 7314 (Yaqoob et al. 1996) shows more variability in the wing than the core,
as predicted. This may also be true for MCG-6-30-15 on the shortest time scales (Iwasawa et al. 1996). Our results show no apparent change in profile, which is to be expected over the longer observation baseline (1 yr), where the total flux of the line should track the continuum. The stability of the line profile over this time period suggests that there are no gross changes in the geometry of the system (accretion disk and X-ray source). Further progress requires better-sampled data with high signal-to-noise-ratio, but the results so far suggest that, even with current instrumentation, such observations would be most rewarding.

ACKNOWLEDGMENTS

We thank the ASCA team for their operation of the satellite, and the ASCA GOF at NASA/GSFC for helpful discussions. We acknowledge the financial support of the National Research Council (KN) and Universities Space Research Association (IMG,TJT). This research has made use of data obtained through the HEASARC on-line service, provided by NASA/GSFC.

REFERENCES

Tanaka, Y., et al., 1995, Nat, 375, 659