NARROW COMPONENTS WITHIN THE Fe Kα PROFILE OF NGC 3516: EVIDENCE OF THE IMPORTANCE OF GENERAL RELATIVISTIC EFFECTS?

T. J. Turner, R. F. Mushotzky, T. Yaqoob, I. M. George, S. L. Snowden, H. Netzer, S. B. Kraemer, K. Nandra, and D. Chelouche

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ABSTRACT

We present results from a simultaneous Chandra High Energy Transmission Grating and XMM-Newton observation of NGC 3516. We find evidence of several narrow components of Fe Kα along with a broad line. We consider the possibility that the lines arise in a 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\,\AA{} and 175\,\AA{}, perhaps as a result of 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 (AGNs) are believed to be powered by the accretion of material onto a supermassive black hole. Intrinsically narrow emission lines from the accretion disk are predicted to produce double-horned profiles as a result of 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 effects 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 then gives a broad (FWHM \( \Delta E / E \sim 0.3 \)) asymmetric profile (Laor 1991; Fabian et al. 2000). The X-ray bandpass contains the strongest such line, Fe Kα, emitted via fluorescence or recombination processes between 6 and 7 keV, depending on the ionization state of the gas. This line is commonly observed in AGNs (e.g., Nandra et al. 1997) with both narrow (Yaqoob et al. 2001) and 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 controversy as to the origin of the broad-line component, with broadening mechanisms such as Comptonization (Misra & Sultaria 1999; Misra & Kembhavi 1998) being suggested along with other possibilities (e.g., Schurch et al. 2002; Zdziarski, Johnson, & Magdziarz 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 \( \sim 4 \) improvement in energy resolution at 6 keV compared with detectors flown previously, allowing the isolation of contributions to the profile from weak narrow features. The European Photon Imaging Camera (EPIC) CCDs on board XMM-Newton (hereafter referred to as XMM) yield a 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 that 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 and 12 UT 02:19:22 overlapped an XMM observation covering November 09 UT 23:12:51–11 UT 10:54:19 and a Rossi X-Ray Timing Explorer (RXTE) observation covering November 11 UT 10:05:36–UT 11:10:56 (Fig. 1). Chandra data were reprocessed using CALBD v2.6 and CIAO v2.1, removing bad pixels, columns, periods of high background, and events with detector “grades” not equal to 0, 2, 3, 4, or 6; yielding an exposure of \( \sim 75 \) ks. The EPIC data reduction pipeline was run with SAS v5.2.0. 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 0–12 (MOS) and 0–4 (PN) were selected. Spectra were extracted from a cell \( \sim 0.94 \) in 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). Reflection Grating Spectrometer data will be presented in a later paper. The RXTE observation of 3.5 ks overlapped the XMM and Chandra data as shown (Fig. 1).
3. THE X-RAY SPECTRUM

We found NGC 3516 to have a flux $F_{2-10\text{ keV}} \sim (1.3-1.5) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$, the lowest observed, first exhibited during a Chandra Low Energy Transmission Grating observation (Netzer et al. 2002). XMM data reveal a flat spectrum across 2–10 keV, with evidence of 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 ~60 ks into the observation. The second segment of XMM data were fitted with the entire Chandra data set 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 High Energy Grating are combined with those of the Medium Energy Grating (MEG) (up to 6.5 keV). Fe Kα emission is evident with a strong peak at a rest energy of 6.41 keV. The associated Fe Kβ line is seen at 7.06 keV, consistent with the expected strength of ~11% of the Kα flux. The Fe Kα component has a width of FWHM ~ 40 eV and is constant in flux over the observation. During the latter part of the XMM observation (T2), PN data hint at a double-line peak, but MOS data do not confirm it, and the HETG data are ambiguous. The constancy in flux, width, and energy indicate that 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 from the accretion flow; thus, we do not consider this component or the associated Kβ line further.

Most importantly, additional and unexpected lines are evident at 5.57 and 6.22 keV. The line widths are consistent with zero, with upper limits FWHM ~ 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 HETG. Overlapping XMM data from T2 (Fig. 2b) confirm the existence of a feature at 6.2 keV and show other features between 6.8 and 6.9 keV in the XMM data (Figs. 2b and 2c).

Table 1 details line fluxes obtained from the HETG and two subsets of XMM data, revealing variability in the lines at 5.6 and 6.2 keV at greater than 99% confidence. The “difference spectrum” (Fig. 2d, i.e., the spectrum from T2 minus that from T1, further highlights the variable components, confirming changes in the line profile at greater than 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 are weighted to a later time). Binning the line coarsely illustrates that Chandra (Fig. 2e) and XMM (Fig. 2f) data reveal a broad component (which will be detailed in a later paper) of equivalent width ~800 eV (using a Gaussian model, the addition of which yielded $\chi^2 = 200$ for 1483 degrees of freedom). Figure 2f shows that the broad component of the line maintains an approximately 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 6.2 keV is 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 Cr xxiii and Mn xxiv could be enhanced to a detectable level. The observed Cr-to-Mn ratio, however, is inconsistent with the spallation model (Skibo 1997). 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, comparison of Figures 2b and 2c demonstrates that the complexity of the profile is due to the appearance of emission features during some time intervals. If the emission line at 5.6 keV is from infalling neutral gas, the implied velocity must be greater than 40,000 km s$^{-1}$. Infalling gas would likely have to be ionized such that the resonance line...
Fig. 2.—X-ray data/model ratios in the Fe Kα regime. The model is a power-law continuum with $\Gamma \sim 1.2$. Data from the high state are shown in panels a (HETG) and b (XMM). HETG data are the sum of the positive and negative first-order grating spectra (plus MEG data up to 6.5 keV). Also, XMM data from the low state are shown in panel c, and the difference spectrum (the high-state minus the renormalized low-state spectra for PN, MOS1, and MOS2) is compared with a power-law fit in panel d (XMM data alone). Panel e shows the coarsely binned HETG data, and panel f shows the XMM data (T2: blue squares, T1: green crosses); we combine data from PN, MOS1, and MOS2, which agree when viewed individually.
opacity and the bound-free opacity would be 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 blueshifted lines from Fe xxvii Lyα (6.97 keV) and Fe xxv 1s2p−1s2 (6.69 keV), with an outflow velocity of ≈0.27c (Marshall, Canizares, & Schulz 2002). The narrow lines at 5.6 eV and 6.2 keV cannot be explained by H- and He-like Fe emission from a single flow. However, if the lines are Ni xxv 1s2p−1s2 (7.789 keV) and Fe xxvii Lyα, the redshifts are consistent with a velocity of ≈0.25c (assuming a disk inclination of 38°, Wu & Han 2001). In fact, Marshall et al. (2002) report the detection of relativistically redshifted Ni xxvii in SS 433. Wang et al. (2000) predict that blobs of gas originating from disk instabilities will initially be fully ionized but will show line emission via recombination sometime after ejection (approximately days, assuming T ≈ 10⁸ K and n_e ≈ 10¹⁰ cm⁻³). Hence, it is possible that these emission lines are recombination lines of He-like Ni and H-like Fe, although we require an overabundance of Ni or a peculiar ionization balance in the recombining gas. Since there are no blueshifted features (at 6.21 and 9.19 keV), the jet must be one-sided, perhaps an example of the MHD-driven jets suggested by Chagelishvili, Bodó, & 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. 2000; Misra 2001) whether thermal Comptonization of a narrow Fe Kα line could explain the broad components in AGNs. 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 AGNs, 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 that they originate in material with an organized kinematic structure such as the accretion disk, arising from narrow annuli or hot spots (Semerak, Karas, & de Felice 1999; Nayakshin & Kazanas 2001). Models for the reverberation of flares across the disk predict narrow features (Young & Reynolds 2000), but they should only exist for a few hundred seconds. If the gas is ionized, the 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. Assuming the central regions of NGC 3516 to be inclined at 38° (Wu & Han 2001), the lines would be produced between 3 and 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_orb ≈ (r/R_g)³/²M_g] are 1–2.3 hr for (3–5)R_g (around a black hole mass of M_g ≈ 2.3 × 10⁷ M_☉) 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. The peak at 5.6 keV could be the red horn of a line from ~35R_g (a weak peak close to 6.8 keV may be the blue horn associated with this). The 6.2 and 6.5 keV peaks could be due to emission from ~175R_g (Fig. 3). At these radii, the feature widths match predictions for illuminated annuli or orbiting blobs (175R_g may be outside the disk structure). Emission from a restricted area on the disk was previously suggested by Iwasawa et al. (1999) based on a flare state in MCG −6-30-15. Thus, the phenomenon observed here may be generally applicable to AGNs. The lack of strong features blueward of 6.4 keV is a problem for all the models discussed here. Occultation (McKernan & Yaqoob 1998), in which different regions of the disk become visible at different times, may be important.

In summary, new data show spectral features most likely explained as Fe Kα lines, modified by relativistic effects. An increase in the 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 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. We are grateful to the Chandra, XMM, and RXTE satellite operation teams for the coordination of the multiwave band observations. We thank Craig Markwardt for production of the RXTE spectrum. T.J. Turner acknowledges support from NASA grant NAG5-7538. This research was supported by the Israel Science Foundation (grant 545/00).

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