X-RAY CHARACTERISTICS OF NGC 3516: A VIEW THROUGH THE COMPLEX ABSORBER

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ABSTRACT

We consider new Suzaku data for NGC 3516 taken during 2009 along with other recent X-ray observations of the source. The cumulative characteristics of NGC 3516 cannot be explained without invoking changes in the line-of-sight absorption. Contrary to many other well-studied Seyfert galaxies, NGC 3516 does not show a positive lag of hard X-ray photons relative to soft photons over the timescales sampled. In the context of reverberation models for the X-ray lags, the lack of such a signal in NGC 3516 is consistent with flux variations being dominated by absorption changes. The lack of any reverberation signal in such a highly variable source disfavors intrinsic continuum variability in this case. Instead, the colorless flux variations observed at high flux states for NGC 3516 are suggested to be a consequence of Compton-thick clumps of gas crossing the line of sight.

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

Online-only material: color figure

1. INTRODUCTION

Signatures of ionized gas are commonly observed in Seyfert galaxies. Well-studied sources reveal multiple zones of X-ray-absorbing gas covering a range of ionization state, column density, covering fraction, and kinematics (e.g., Netzer et al. 2003; Behar et al. 2003; Kaspi et al. 2002; Steenbrugge et al. 2005; Blustin et al. 2005, 2007; McKernan et al. 2007). The detection of deep K-shell absorption lines from very highly ionized species of Fe (e.g., Reeves et al. 2004; Kaspi et al. 2002; Turner et al. 2008) has shown that X-ray-absorbing gas can be spectroscopically traced up to equivalent hydrogen column densities $N_{\text{H}} \sim 10^{22} \text{ cm}^{-2}$. The possible existence of circunuclear gas at high column densities is of great interest with regard to understanding the mass flow around the black hole and energetic considerations for the system. UV spectroscopy unequivocally shows an active galactic nucleus (AGN) to possess complex absorption systems and so the presence of a complex of X-ray absorbers should be unsurprising.

The systematic spectral hardening exhibited by Seyfert-type AGNs as they drop in X-ray flux (e.g., Papadakis et al. 2002; Pounds et al. 2004a, 2004b; Vaughan & Fabian 2004; Miller et al. 2007, 2008; Turner et al. 2008) can be modeled by changes in covering fraction of X-ray-absorbing gas. There are a few cases where changes in individual lines trace rapid changes in the X-ray absorber. For example, an absorption line from Fe xxv detected in NGC 3783 varies on timescales of days (Reeves et al. 2004), likely originating $\sim 0.1$ pc from the nucleus. In NGC 1365, variable absorption lines have been detected from Fe xxv and Fe xxvi supporting a picture in which the nucleus suffers variable obscuration by an absorber whose covering fraction changes on short timescales (Risaliti et al. 2005, 2007).

In the broad-line Seyfert 1 galaxy (BLSy1) NGC 3516 ($z = 0.008836$; Keel 1996), X-ray data covering 0.5–10 keV have revealed a strong signature from a variable X-ray-absorbing outflow. X-ray-grating data from Chandra HETG and XMM RGS show discrete absorption features tracing a range of column densities, ionization states, and velocity components for the gas (e.g., Turner et al. 2008; Mehdipour et al. 2010). Here, we present new Suzaku data from NGC 3516, taken during 2009 October. We also reconsider recent X-ray observations of this source, seeking to reconcile the spectral and timing behavior and thus elucidate the true nature of the X-ray signatures of this AGN.

2. THE SUZAKU OBSERVATIONS

Four co-aligned Suzaku (Mitsuda et al. 2007) telescopes focus X-rays on to CCD cameras comprising the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007). XIS units 0, 2, and 3 are front-illuminated (FI), while XIS 1 is a back-illuminated CCD. XIS 1 has an enhanced soft-band response but lower area at 6 keV than the FI CCDs as well as a larger background level at high energies. XIS 2 failed on 2006 November 9 and hence was not used. Suzaku also carries a non-imaging, collimated Hard X-ray Detector (HXD; Takahashi et al. 2007), whose positive-intrinsic-negative (PIN) detector provides useful AGN data typically over the range of 15–70 keV.

A Suzaku observation of NGC 3516 was made on 2009 October (ObsID 704062010) and the data were reduced using v6.9 of HEASOFT. We screened the XIS and PIN events to exclude data during passage through the South Atlantic Anomaly, starting and ending within 500 s of entry or exit. Additionally, we excluded data with an Earth elevation angle less than 10$^\circ$ and cutoff rigidity $> 6$ GeV. The source was observed at the nominal center position for the HXD. FI CCDs were in $3 \times 3$ and $5 \times 5$ edit modes, with normal clocking mode. We selected good events with grades 0, 2, 3, 4, and 6 and removed hot and flickering pixels using the SISCLEAN script. The spaced-row charge injection was utilized. The exposure times were 222 ks per XIS unit and 178 ks for the PIN. XIS products were extracted from circular regions of 3$''$ radius, while background spectra were extracted from a region of radius 2$''$ (offset from the source and avoiding the chip corners, where there are data from the calibration sources).
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Table 1

| Observation                  | Flux (0.5–2 keV) | Flux (2–10 keV) | Flux (10–50 keV) |
|------------------------------|------------------|-----------------|------------------|
| 2001 Apr XMM-Newton          | 0.49             | 2.27            | ...              |
| 2001 Nov XMM-Newton          | 0.29             | 1.63            | ...              |
| 2005 Oct Suzaku              | 0.13             | 2.30            | 8.11             |
| 2006 Oct XMM-Newton/Mean     | 1.75             | 4.36            | ...              |
| 2006 Oct XMM-Newton/0401      | 2.21             | 5.08            | ...              |
| 2006 Oct XMM-Newton/0501      | 2.02             | 4.49            | ...              |
| 2006 Oct XMM-Newton/0601      | 1.04             | 3.62            | ...              |
| 2006 Oct XMM-Newton/1001      | 1.95             | 4.44            | ...              |
| 2009 Oct Suzaku              | 0.30             | 1.30            | 3.90             |

Note. The observed flux in erg cm$^{-2}$ s$^{-1}$.

For the 2009 HXD PIN analysis, we used the model “D” background (released 2008 June 17). The time filter resulting from screening the observational data was applied to the background events model. The ftool hxdpinxbpi was used to create a PIN background spectrum from the screened background data. hxdpinxbpi takes account of the form and flux level of the cosmic X-ray background (Boldt & Leiter 1987; Gruber et al. 1999) in the Suzaku PIN field of view. We used the response file ae_hxd_pinxinome3_20090826.rsp for spectral fitting.

During the 2009 Suzaku observation, NGC 3516 was found to have source count rates $0.507 \pm 0.001$ (summed XIS 0, 3 over 0.75–10 keV) and $0.049 \pm 0.002$ (PIN over 15–50 keV) counts s$^{-1}$. The background was 5% of the total XIS count rate in the full band. The source comprised 9% of the total counts in the PIN band. The source fluxes for recent observations of NGC 3516 are shown in Table 1.

Spectral fits utilized data from XIS 0 and 3 in the energy range 0.75–10 keV and from the PIN over 20–50 keV. Data in the range 1.75–1.9 keV were also excluded from the XIS spectral analysis owing to uncertainties in calibration around the instrumental Si K edge. We note that data can be used down to lower energies, $\sim 0.3$ keV, for timing analysis. XIS 1 was not used owing to the higher background level at high energies. XIS data were binned at the HWHM resolution for each instrument, optimal for detection of spectral features, while PIN data were binned to be a minimum of 5$\sigma$ above the background level for the spectral fitting. In the spectral analysis, the PIN flux was increased by a factor of 1.18 for the new data, appropriate for the cross calibration of instruments for the 2009 observation. The new data were considered in conjunction with those from 2005, whose screening and data reduction are described by Markowitz et al. (2008).

3. SPECTRAL-FITTING RESULTS

Chandra images of NGC 3516 (George et al. 2002) have shown an extended soft X-ray emission component contributing an observed flux $F_{0.1-2\text{ keV}} \sim 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ within $\sim 2$ kpc (assuming $H_V = 73$ km s$^{-1}$ kpc$^{-1}$ throughout). In addition, there is a known off-nuclear X-ray source, CXOU 110648.1+723412 (George et al. 2002), that cannot be separated from the nuclear emission using Suzaku. However, these two provide only a small fraction of the total soft-band flux for the epochs considered here.

For an immediate visual comparison of data from recent X-ray observations of NGC 3516, we plotted the 2009 XIS spectral data with the 2005 Suzaku observation and other observations made using XMM overlaid (Figure 1). This comparison reveals that during 2009, Suzaku found NGC 3516 in a relatively low flux state. The data show that the line-of-sight absorption is obviously changing between epochs for NGC 3516. Although the hard X-ray flux levels are very similar in the 2005 Suzaku and 2001 April XMM-Newton data, the former shows a large amount of extra absorption compared to the latter. The lowest level of hard X-ray flux is observed in the new data from 2009, although at this epoch the absorption appears to be also relatively low. It is clear that the source cannot be simply described by a response in the ionization of the absorbing gas to changes in the continuum flux.

3.1. Fitting Absorption Models

From detection of discrete absorption lines and from broad spectral curvature, Turner et al. (2008) found evidence for a multi-zoned X-ray absorber in a joint XMM-Newton/Chandra campaign during 2006. Markowitz et al. (2008) also found complex absorption to be required to fit the spectrum of NGC 3516 observed by Suzaku during 2005 (and in that spectral data with the 2005 Suzaku observation and other observations made using XMM overlaid (Figure 1). This comparison reveals that during 2009, Suzaku found NGC 3516 in a relatively low flux state. The data show that the line-of-sight absorption is obviously changing between epochs for NGC 3516. Although the hard X-ray flux levels are very similar in the 2005 Suzaku and 2001 April XMM-Newton data, the former shows a large amount of extra absorption compared to the latter. The lowest level of hard X-ray flux is observed in the new data from 2009, although at this epoch the absorption appears to be also relatively low. It is clear that the source cannot be simply described by a response in the ionization of the absorbing gas to changes in the continuum flux.

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UV spectroscopy (Kraemer et al. 2002). HETG spectra required grating spectroscopy (Turner et al. 2006) and from Chandra three different covering factors. The outermost layer is Zone 1, covered by zones of an intrinsic absorbing gas (Table 2) having xstar using σ absorber table was created with effective micro-turbulence epochs (Kraemer et al. 2002). The total column density for Zone 1 is consistent with two gas components to account for the soft-band absorption (Kalberla et al. 2005). The fit yielded an underlying photon index $\Gamma \approx 2.22 \pm 0.04$ covered by zones of an intrinsic absorbing gas (Table 2) having three different covering factors. The outermost layer is Zone 1, comprising low-ionization gas, as established in NGC 3516 from Chandra grating spectroscopy (Turner et al. 2006) and from UV spectroscopy (Kraemer et al. 2002). HETG spectra required two gas components to account for the soft-band absorption features measured during 2006 (Turner et al. 2008). For the joint Suzaku fit, we also found that the fit was significantly improved ($\Delta \chi^2 = 63$) by allowing the low-ionization zone to have two components (Table 2 Zones 1a and 1b having the same covering fraction). The total column density for Zone 1 is consistent with the sum of the UV-absorbing components measured at other epochs (Kraemer et al. 2002). Additional absorbing zones were found (Table 2) with column densities $\sim 2 \times 10^{23} \text{ cm}^{-2}$ and $\sim 2 \times 10^{24} \text{ cm}^{-2}$, both having log $\xi \sim 2$. The covering fraction of the Compton-thick zone is around 70% in 2005 and 2009 spectra. We note that this hard component can, alternatively, be modeled as reflection, as shown by Markowitz et al. (2008).

xstar does not calculate the scattered component of X-ray flux from the absorbing gas; however, it does calculate the re-emitted line spectrum and we included such a component in the model, placing it behind the Zone 1 absorber complex. With such a placement, the re-emission spectrum accounts for the strength of Fe Kα emission without overpredicting the soft line emission (that is somewhat suppressed by absorption). The ionization parameter of the emitting gas was left free to encompass the possibility that emission arises in a gas component other than one of the absorbers and indeed, the fitted ionization parameter was found to be $\xi = 1.53 \pm 0.10$, different from the absorbing gas. The fit gave a reduced $\chi^2 = 1.24/358$ degrees of freedom (dof). Interestingly, the emission spectrum fitted here is consistent with the ionization state found for soft-band lines in XMM-Newton RGS grating data (Turner et al. 2003).

We stress that the absorption model does not overpredict the Fe Kα flux, or the flux of any emission line, even if the gas zones are assumed to fully cover the continuum source. The strength of the emission from the absorbing gas depends on the gas geometry, column density, and covering/filling factors. Even large column densities for the absorber can result in a small predicted line equivalent width (Miller et al. 2009; Yaqoob et al. 2010), when there is expected to be a large opacity at the line energy. It is not surprising that the absorber emission has not been isolated in these data, given the gas geometry suggested in this case.

In this absorption model, the covering fractions of the gas layers varied significantly between epochs (Table 2). Importantly, Zone 2 had a larger covering fraction during 2005 (99%) than during 2009 (86%), despite the hard-band continuum flux being a factor of two higher (Figure 1). The most highly ionized zone detected at any epoch is that traced by absorption lines from Fe xxv and Fe xxvi whose depths indicate an origin in the gas having $N_{\text{H}} \sim 3 \times 10^{23} \text{ cm}^{-2}$ and log $\xi \sim 4.3$ (Turner et al. 2008) These lines were detected in XMM-Newton and Chandra data from 2006 and in Suzaku data from 2005; however, they were not detected during the Suzaku observation of 2009, with limits on the equivalent widths of (narrow) Fe xxv and xxvi absorption found to be <5 eV and <20 eV, respectively.

The absorption modeling and covering fraction changes are fundamentally consistent with the conclusions of Markowitz et al. (2008) and Turner et al. (2008), i.e., the source has a complex absorber and changes in covering by a high column of gas $\sim 10^{23} \text{ cm}^{-2}$ of “intermediate” ionization (in terms of the X-ray-absorbing zones detected in NGC 3516) dominate the spectral variability. Small differences between the fit of Markowitz et al. (2008) and that presented here arise because we are fitting under the joint constraints from 2009 and 2005 epochs, and also because we utilize a new version of xstar and use a slightly different model construction.

Constraining the covering fractions of the gas to be the same for 2005 and 2009, allowing only the column densities and ionization states of the layers to be free for each epoch, does not provide a satisfactory joint fit to the two epochs ($\chi^2 = 4.8/355$ dof.). It is clear that the source cannot be parameterized satisfactorily without invoking such a mode of variation.

Small improvements to the fit can, of course, be obtained by allowing the absorber column densities and ionization states to also vary between epochs. However, as Suzaku cannot distinguish which of the layers of gas are varying, we did not find it useful to pursue this line of consideration further.

### 3.2. Fe Kα Line Variability

To test for variability in the Fe Kα line emission, we re-fit the 4.0–7.5 keV data using a simple absorbed power-law model for the local continuum. The line was modeled using a simple

| Zone | $\log \xi$ | $N_H^a$ | $C(2005)^b$ | $C(2009)^b$ |
|------|-----------|----------|-------------|-------------|
| 1a   | 0.17 ± 0.28 | 0.48$^{+1.18}_{-1.16}$ | 99% ± 1% | 97% ± 3% |
| 1b   | 0.51$^{+0.25}_{-0.10}$ | 1.57$^{+0.64}_{-0.17}$ | ... | ... |
| 2    | 2.90$^{+0.01}_{-0.02}$ | 19.0$^{+0.40}_{-0.61}$ | 99% ± 1% | 86% ± 1% |
| 3    | 2.05 ± 0.05 | 200±6 | 70% ± 2% | 72%$^{+3\%}_{-2\%}$ |

Notes. A column of neutral gas covered all components, representing the Galactic absorption; see the text for details. An additional column of ionized gas covered all components during 2005 only, with $N_H = 3 \times 10^{23} \text{ cm}^{-2}$ and $\log \xi = 4.3$; see the text for additional details. Errors are calculated at 90% confidence. The remaining flux not accounted for in the table travels along a line of sight that is not covered by the intrinsic absorbers.

a Column density in units of $10^{22} \text{ atom cm}^{-2}$

b Percentage covering.

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**Table 2**

Partial Covering Model

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Gaussian profile. Initial fits found the line width to be consistent with the high energy grating (HEG) value $\sigma = 40$ eV, at all epochs (Turner et al. 2008) and so the fits were rerun with the line width fixed at that value.

The joint 2005/2009 Suzaku fit yielded a peak energy for the line $E = 6.40 \pm 0.06$ keV. The normalization of the Fe Kα line was $5.75 \pm 0.24 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ (an equivalent width of 164 eV against the observed continuum) during 2005 and $4.16^{+0.33}_{-0.32} \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ (equivalent width 253 eV) during 2009. Thus, comparison between the two mean spectra observed using Suzaku reveals strong evidence (>99.9% confidence) for variability in Fe Kα line flux over timescales of years.

To investigate the line behavior on shorter timescales, the 2001 April, 2001 November, and 2006 XMM-Newton data were re-fit with the new model. Fe Kα line fluxes are detailed in Table 3. In addition to these fits, the individual ObsIDs comprising the XMM-Newton data for 2006 were fit individually, yielding Fe Kα fluxes sampled on timescales of days; however, no significant variability was detectable on such a timescale (Table 3).

### 4. TIMING ANALYSIS

We examined the hard- (4.0–7.5 keV) and soft-band (0.3–1 keV) light curves from the Suzaku observations. As was evident from the spectral analysis (Figure 2), the hardness ratio is very different for the two epochs (Figure 3).

The best constraints on the timing properties of NGC 5316 are currently offered by the combined data of 2006. At that epoch, the source was bright and, taken together, the XMM-Newton and Chandra exposures provide a long baseline of coverage (Turner et al. 2008). We re-constructed the combined XMM-Newton/Chandra light curve in selected energy bands (Figure 4). The effective areas and spectral responses of the XMM-Newton and Chandra data differ: to create a single light curve, the expected XMM-Newton and Chandra count rates in narrow energy bins were calculated from the mean spectral model. Next, the time-dependent observed XMM-Newton count rate in those energy bins was rescaled to the expected Chandra count rate using that mean conversion between instruments. The light curve in broader energy bands was then calculated by summing the renormalized values, propagating XMM-Newton statistical errors, taking account of the energy-dependent re-normalization. By scaling to the Chandra instrument, the uncertainties on the

### Table 3

| Observation             | Normalization$^a$ |
|-------------------------|-------------------|
| 2001 Apr XMM-Newton     | $3.34^{+0.40}_{-0.34}$ |
| 2001 Nov XMM-Newton     | $4.05^{+0.25}_{-0.23}$ |
| 2005 Oct Suzaku         | $5.75 \pm 0.24$    |
| 2006 Oct XMM-Newton/Mean| $3.94 \pm 0.17$    |
| 2006 Oct XMM-Newton/0401 | $3.51^{+0.67}_{-0.73}$ |
| 2006 Oct XMM-Newton/0501 | $4.00^{+0.61}_{-1.05}$ |
| 2006 Oct XMM-Newton/0601 | $4.25^{+0.47}_{-0.83}$ |
| 2006 Oct XMM-Newton/1001 | $3.96^{+0.82}_{-0.80}$ |
| 2009 Oct Suzaku         | $4.16^{+0.33}_{-0.32}$ |

Notes. For these fits, the line energy was fixed at 6.4 keV and the line width at $\sigma = 40$ eV, as determined from HEG data (Turner et al. 2008). Errors were calculated at 90% confidence.

$^a$ Normalization of a Gaussian model fit to the Fe Kα line, in units $10^{-5}$ photons cm$^{-2}$ s$^{-1}$.
Figure 3. *Suzaku* XIS0 + 3 time series in 2048 s bins, from the 2005 and 2009 *Suzaku* observations. Red points represent 4–7.5 keV and black the 0.3–1 keV band.

Figure 4. Light curve in 2048 s bins from 2006 *XMM-Newton* pn and *Chandra* HETG data with soft (black: 0.3–1.0 keV) and hard bands (red: 4.0–7.5 keV) overlaid. The *XMM-Newton* light curve rates have been re-normalized to the *Chandra* count rate, and HETG points can be recognized most easily by the relatively large uncertainties on the count rate.

Figure 5. Lag spectra for 2006 *XMM-Newton* data, calculated for 4–7.5 keV vs. 0.3–1 keV. On this plot, positive values of $\tau$ would represent a lag of hard photons relative to the soft.

to high frequencies. In contrast to the long *XMM-Newton*/ *Chandra* campaign of 2006, the *Suzaku* data yielded a relatively short baseline, relatively low amplitude of variability, and did not yield conclusive results for the lag spectra. Intriguingly, the lag spectra for 2006 data from NGC 3516 showed no positive time lags (Figure 5). At the lowest frequencies sampled there is weak evidence for negative time lags (soft band lagging the hard band), but as the timescales concerned are approaching the longest periods sampled by these observations, caution is required in their interpretation, and independent observations are required to confirm their reality.

5. DISCUSSION

5.1. Spectroscopy Results

Comparison of recent X-ray spectra of NGC 3516 shows that the source has a relatively hard spectrum at some epochs of high X-ray flux. A review of historical X-ray observations of NGC 3516 confirms that there have been numerous epochs during which the source has shown heavy absorption by low-ionization gas, often at high levels of continuum flux (Kruper et al. 1990; Ghosh & Soundararajaperumal 1991; Kolman et al. 1993; Guainazzi et al. 2001). The covering changes for the absorbing gas are not well correlated with the observed X-ray continuum flux in NGC 3516, implying that, in addition to the flux variations that are a direct result of obscuration changes, one must invoke either intrinsic continuum variations or “colorless” variability originating from the passage of Compton-thick blobs of gas across the line of sight. Reverberation results favor the latter possibility (see Section 5.2) and in that case the additional component of the model forms a natural extension to the absorber spectral model.
The light-bending model of Miniutti & Fabian (2004), which attempts to account for flux and spectral variability in AGNs by varying the distance of the continuum source perpendicularly from the accretion disk, cannot naturally account for behavior where the source spectrum is found to be hard at a high flux state. Adherence to this model would require an additional variability mechanism to account for all of the X-ray states observed in NGC 3516. Invocation of another source of continuum mechanism to account for all of the X-ray states observed in NGC 3516 shows some of the strongest and most variable intrinsic blueshifted UV absorption lines of any Seyfert 1 galaxy (Kolman et al. 1993; Goad et al. 1999). The C iv absorption is particularly deep and broad and has led some to compare the systems in NGC 3516 to those in broad absorption line QSOs (Ulrich 1988). UV absorption features arise in multiple zones having covering fractions <1 (Kraemer et al. 2002). Kraemer et al. (2002) resolve several kinematic components of absorption in the UV lines. Those authors also isolated the zones of gas having signatures spanning both the UV and X-ray regimes, confirming an association between the two bands that had been previously suggested (Guainazzi et al. 2001). Estimates placed the C iv origin at \( \sim 10^{16} \) cm (Koratkar et al. 1996) with other lines arising out to \( \sim 10^{18} \) cm from the central source (Kraemer et al. 2002).

Similar to the Seyfert Type 2 AGN, NGC 3516 shows a bipolar morphology for the narrow-line-region (NLR) gas (Pogge 1989). In NGC 4151, Space Telescope Imaging Spectrograph data show evidence for fast-moving clouds existing over a wide angle and originating close to the nucleus (Hutchings et al. 1999; Crenshaw & Kraemer 2007), possibly collimating the nuclear radiation that excites the NLR gas (Kraemer et al. 2008). A similar model may apply to NGC 3516, where a toroidal distribution of outflowing clouds might collimate the nuclear radiation. Such a toroidal gas distribution could provide X-ray absorption and emission features from different zones within the flow. If our view of NGC 3516 intercepts the edge of the collimating flow we might naturally expect the source behavior to be more variable than sources viewed at face-on or edge-on orientations.

In the context of the partial-covering model, variations of the Fe Kα flux may arise if the line-emitting region suffers variable obscuration. However, the line flux also depends on the illuminating flux reaching the emitting gas and so the line behavior might be expected to appear complex in a multi-layer absorber model.

HEG data find the Fe Kα emitter to have a bulk velocity consistent with zero (Turner et al. 2008). The HEG constraint on the line width is 25 eV < \( \sigma < 50 \) eV, equivalent to FWHM velocity broadening in the range 3000–6000 km s\(^{-1}\). For gas in a Keplerian orbit, the line width corresponds to an origin (4–17) \( \sin^2 i \) light days from the nucleus (where \( i \) is the angle of inclination of the orbital plane, assuming a black hole mass \( 2.95 \times 10^7 M_\odot \); Nikolajuk et al. 2006).

Of course, the partial-covering model does not rule out a response of the absorbing gas to changes in the incident flux: it is inevitable (and therefore predicted) that covering changes for inner zones of a complex absorber modify the flux and spectral shape of the continuum reaching zones further out, possibly leading to measurable changes in the ionization balance of the gas.

As discussed for the 2006 XMM-Newton/Chandra data (Turner et al. 2008), numerous absorption lines are detected in the HETG and RGS gratings, providing a firm basis for the absorption model in NGC 3516. The combined signature of multi-zoned X-ray absorbers produces curvature in the observed spectral shape, while spectral variability can be explained by changes in the covering fraction of the layers. Although current X-ray data do not allow the gas covering fraction to be measured directly from the absorption lines, this quantity can be constrained from the broad X-ray spectral curvature.

This X-ray absorption model comprises a compelling extension of the well-studied UV absorption systems. NGC 3516 shows some of the strongest and most variable intrinsic blueshifted UV absorption lines of any Seyfert 1 galaxy (Kolman et al. 1993; Goad et al. 1999). The C iv absorption is particularly deep and broad and has led some to compare the systems in NGC 3516 to those in broad absorption line QSOs (Ulrich 1988). UV absorption features arise in multiple zones having covering fractions <1 (Kraemer et al. 2002). Kraemer et al. (2002) resolve several kinematic components of absorption in the UV lines. Those authors also isolated the zones of gas having signatures spanning both the UV and X-ray regimes, confirming an association between the two bands that had been previously suggested (Guainazzi et al. 2001). Estimates placed the C iv origin at \( \sim 10^{16} \) cm (Koratkar et al. 1996) with other lines arising out to \( \sim 10^{18} \) cm from the central source (Kraemer et al. 2002).  

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5.2. Timing Results

There has been mounting support for the idea that large amplitude and rapid X-ray flux variations are caused by changes in the line-of-sight absorption (Boillot et al. 1997; Guainazzi et al. 1998; Tanaka et al. 2004). In such a picture, the low/hard states of AGNs may be attributable to increases in X-ray obscuration, as suggested for NGC 3516 based on BeppoSAX and ASCA data (Nogami et al. 2004). Deep dips in X-ray flux have been traced by the light curves of MCG-6-30-15 (McKernan & Yaqoob 1998) and NGC 3516 (Turner et al. 2008), where data allow us to track the apparent ingress through to the egress of an occultation event. Interestingly, the detailed dip profiles match the profile of dip events in some X-ray binaries, e.g., GRO 1655−40 (Tanaka et al. 2003), where in that case the dip was attributed to an increase in the covering fraction of a complex X-ray absorber. Spectral variability in Cir X-1 has also been attributed to changes in covering of a complex absorber (Brandt et al. 1996). The deep dips in NGC 3516 and MCG-6-30-15 are similarly consistent with occultation events. The large number of similarities in observed timing and spectral properties of AGNs and stellar binary systems suggest that complex and variable absorption dominates the observed X-ray properties for accreting systems over stellar to galaxy size scales. This, in turn, suggests that the often-outflowing absorber is closely related to the accretion process, and therefore of the highest importance in understanding the fundamental mechanisms in these systems.

Close study of key sources is required to decouple intrinsic continuum variations from absorption effects. The 2006 XMM-Newton/Chandra campaign (Turner et al. 2008) showed that in the 0.5−10 keV band, there appear to be two characteristically different modes of X-ray variability: one which results in opacity changes and thus changes in hardness ratio, the other, particularly at high fluxes, which results in no change in hardness ratio. In the context of the complex absorption model, the latter mode may apply when the continuum is uncovered by the fitted absorbers: in the 2006 data this occurred above a flux $F_{2−10} \sim 3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Variability above this threshold was attributed either to intrinsic variations in the continuum or to changes in covering by Compton-thick “bricks” (Turner et al. 2008).

Recent long X-ray exposures on two bright AGNs have allowed significant progress with regard to our general understanding. Suzaku data from NGC 4051 show that the frequency and energy dependence of the observed time lags can be explained by the effects of reverberation from a thick shell of material extending to ~600 gravitational radii from the continuum source (Miller et al. 2010a). That work was the first interpretation of the previously known positive AGN time lags, which dominate the lag spectra, as arising from reverberation within the X-ray band.

A second important result arises in XMM-Newton data from 1H 0707−495. The source shows lags that oscillate between positive and negative values as a function of temporal frequency of variation. However, in 1H 0707−495 it has also been shown (Miller et al. 2010b) that a simple reverberation model can explain the full set of (positive and negative) lags, requiring no additional physical processes to explain the observed lag sign changes.

Many AGNs show a lag of hard X-ray photons relative to soft, with the lag increasing to decreasing temporal frequency (e.g., McHardy et al. 2004; Papadakis et al. 2001; Markowitz 2005; Arévalo et al. 2006; Dasgupta & Rao 2006; Markowitz et al. 2007; Sriram et al. 2009). However, NGC 3516 shows no such positive lag (Figure 5). In the context of our reverberation model for AGN lags (Miller et al. 2010a, 2010b), the lack of a lag in NGC 3516 is interpreted as an absence of a reverberation signal.

These unusual lag results may be associated with the special sight line at which we observe NGC 3516. The results may be explained if the variations observed during 2006 are attributable predominantly to covering changes of the absorber along our line of sight (i.e., the continuum being intrinsically quasi-constant during those observations), as we would not then expect to see systematic reverberation, which require all lines of sight to vary coherently. Even if the reprocessor subtended a large solid angle to the continuum, there would be no reverberation for the case where there is no intrinsic variation in the continuum. In this case, the PIN-band fluctuations might be attributed to variable obscuration by material having $N_H > 10^{25}$ cm$^{-2}$.

The tentative negative lag observed at low frequencies in NGC 3516 might be explained by the presence of a reprocessed signal in the soft band, rather than in the hard band. Such a soft signal would be expected if we observed the emission spectrum from Compton-thin, ionized layers of the absorber. This suggestion is supported by the presence of significant soft-band line emission at the lowest X-ray flux states.

6. CONCLUSIONS

Comparison of 2009 Suzaku data with historic X-ray observations of NGC 3516 shows that relatively hard X-ray spectral forms are exhibited at some epochs of high X-ray flux. Variable X-ray absorption is necessary to explain the range of states observed: simple changes in the gas ionization state are insufficient to explain the range of properties exhibited by NGC 3516.

While much of the variability below 10 keV may be explained by changes in the modeled X-ray absorber complex, there is a colorless component of variability evident during high flux states. In past work, the colorless flux variations have been suggested to originate as either intrinsic continuum fluctuations, or to be a consequence of the passage of Compton-thick clumps of gas across the line of sight.

NGC 3516 provides a rare example to date of a source showing no significant lag of hard X-ray photons relative to soft photons over the timescales studied. This result may be interpreted as an absence of any hard reverberation signal. If this interpretation is correct, despite a large amount of reprocessing material apparently being present around the nucleus, then it seems likely that the continuum source is not intrinsically strongly variable on the timescales studied. We suggest that even the high-state flux variations may be attributed to Compton-thick clumps crossing the line of sight. The presence of such high-opacity clumps is a natural extension of the complex absorption model that can describe the X-ray spectrum.

The unusual properties of NGC 3516 may be a consequence of our viewing the source at a rare orientation, where our line of sight intercepts the edge of a significant absorber structure that collimates the nuclear radiation leading to the observed biconical structure for the optical NLR gas.

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REFERENCES

Arévalo, P., Papadakis, I. E., Uttley, P., McHardy, I. M., & Brinkmann, W. 2006, MNRAS, 372, 401
Behar, E., Rasmussen, A. P., Blustin, A. J., Sako, M., Kahn, S. M., Kastra, J. S., Branduardi-Raymont, G., & Steenbrugge, K. C. 2003, ApJ, 598, 232
Bhattacharyya, S., & Nandra, K. 2010, MNRAS, 408, 1020
Blustin, A. J., Page, M. J., Fuerst, S. V., Branduardi-Raymont, G., & Ashton, C. E. 2005, A&A, 431, 111
Blustin, A. J., et al. 2007, A&A, 466, 107
Boldt, E., & Leiter, D. 1987, ApJ, 322, L1
Boller, T., Brandt, W. N., Fabian, A. C., & Fink, H. H. 1997, MNRAS, 289, 393
Bond, J. R., Jaffe, A. H., & Knox, L. 1998, Phys. Rev. D, 57, 2117
Brandt, W. N., Fabian, A. C., Dotani, T., Nagase, F., Inoue, H., Kotani, T., & Segawa, Y. 1996, MNRAS, 283, 1071
Crenshaw, D. M., & Kraemer, S. B. 2007, ApJ, 659, 250
Dasgupta, S., & Rao, A. R. 2006, ApJ, 651, L13
Edelson, R., & Nandra, K. 1999, ApJ, 514, 682
George, I. M., et al. 2002, ApJ, 571, 265
Goad, M. R., Koratkar, A. P., Kim-Quijano, J., Korista, K. T., O'Brien, P. T., & Axon, D. J. 1999, ApJ, 524, 707
Gruber, D. E., Matteson, J. L., Peterson, L. E., & Jung, G. V. 1999, ApJ, 520, 124
Guainazzi, M., Marshall, W., & Parmar, A. N. 2001, MNRAS, 323, 75
Guainazzi, M., et al. 1998, A&A, 339, 327
Hutchings, J. B., et al. 1999, AJ, 118, 2101
Kalberla, P. M. W., Burton, W. B., Hartmann, D., Arnal, E. M., Bajaja, E., Mora, R., & Poeppel, W. G. L. 2005, VizieR Online Data Catalog, 8076, 0
Kaspi, S., et al. 2002, ApJ, 574, 643
Keel, W. C. 1996, AJ, 111, 696
Kolman, H., Halpern, J. P., Martin, C., Awaki, H., & Koyama, K. 1993, ApJ, 403, 592
Koratkar, A., et al. 1996, ApJ, 470, 378
Koyama, K., et al. 2007, PASJ, 59, 23
Kraemer, S. B., Crenshaw, D. M., George, I. M., Netzer, H., Turner, T. J., & Mushotzky, R. F., 2002, ApJ, 577, 98
Kraemer, S. B., Schmitt, H. R., & Crenshaw, D. M. 2008, ApJ, 679, 1128
Kruper, J. S., Canizares, C. R., & Urry, C. M. 1990, ApJS, 74, 347
Markowitz, A. 2005, ApJ, 635, 810
Markowitz, A., Papadakis, I., Arévalo, P., Turner, T. J., Miller, L., & Reeves, J. N. 2007, ApJ, 666, 116
Markowitz, A., et al. 2008, PASJ, 60, 277
McHardy, I. M., Papadakis, I. E., Uttley, P., Page, M. J., & Mason, K. O. 2004, MNRAS, 348, 783
McKernan, B., & Yaqoob, T. 1998, ApJ, 501, L29
McKernan, B., Yaqoob, T., & Reynolds, C. S. 2007, MNRAS, 379, 1359
Mehdipour, M., Branduardi-Raymont, G., & Page, M. J. 2010, A&A, 514, A100
Miller, L., Turner, T. J., & Reeves, J. N. 2008, A&A, 483, 437
Miller, L., Turner, T. J., & Reeves, J. N. 2009, MNRAS, 399, L69
Miller, L., Turner, T. J., Reeves, J. N., & Braito, V. 2010a, MNRAS, 408, 1928
Miller, L., Turner, T. J., Reeves, J. N., George, I. M., Kraemer, S. B., & Wingert, B. 2007, A&A, 463, 131
Miller, L., Turner, T. J., Reeves, J. N., Lobban, A., Kraemer, S. B., & Crenshaw, D. M. 2010b, MNRAS, 403, 196
Miniutti, G., & Fabian, A. C. 2004, MNRAS, 349, 1435
Mitsuda, K., et al. 2007, PASJ, 59, 1
Netzer, H., Chelouche, D., George, I. M., Turner, T. J., Crenshaw, D. M., Kraemer, S. B., & Nandra, K. 2002, ApJ, 571, 256
Netzer, H., et al. 2003, ApJ, 599, 933
Nikolajuk, M., Czerny, B., Ziolkowski, J., & Gierliński, M. 2006, MNRAS, 370, 1534
Nogami, K., Negoro, H., Hong, S., & Mihara, T. 2004, Nucl. Phys. B, 132, 209
Papadakis, I. E., Nandra, K., & Kazanas, D. 2001, ApJ, 554, L13
Papadakis, I. E., Petrucci, P. O., Maraschi, L., McHardy, I. M., Uttley, P., & Haardt, F. 2002, ApJ, 573, 92
Pogge, R. W. 1989, ApJ, 345, 730
Pounds, K. A., Reeves, J. N., Page, K. L., & O'Brien, P. T. 2004a, ApJ, 605, 670
Pounds, K. A., Reeves, J. N., Page, K. L., & O'Brien, P. T. 2004b, ApJ, 616, 696
Reeves, J. N., Nandra, K., George, I. M., Pounds, K. A., Turner, T. J., & Yaqoob, T. 2004, ApJ, 602, 648
Risaliti, G., Bianchi, S., Matt, G., Baldi, A., Elvis, M., Fabbiano, G., & Zezas, A. 2005, ApJ, 630, L129
Risaliti, G., Elvis, M., Fabbiano, G., Baldi, A., Zezas, A., & Salvati, M. 2007, ApJ, 659, L111
Sriram, K., Agrawal, V. K., & Rao, A. R. 2009, ApJ, 700, 1042
Steenbrugge, K. C., et al. 2005, A&A, 434, 569
Takahashi, T., et al. 2007, PASJ, 59, 35
Tanaka, Y., Boller, T., Gallo, L., Kruij, R., & Ueda, Y. 2004, PASJ, 56, L9
Tanaka, Y., Ueda, Y., & Boller, T. 2003, MNRAS, 338, L1
Turner, T. J., Kraemer, S. B., Mushotzky, R. F., George, I. M., & Gabel, J. R. 2003, ApJ, 594, 128
Turner, T. J., Miller, L., George, I. M., & Reeves, J. N. 2006, A&A, 445, 59
Turner, T. J., Reeves, J. N., Kraemer, S. B., & Miller, L. 2008, A&A, 483, 161
Ulrich, M. 1988, MNRAS, 230, 121
Vaughan, S., & Fabian, A. C. 2004, MNRAS, 348, 1415
Yaqoob, T., Murphy, K. D., Miller, L., & Turner, T. J. 2010, MNRAS, 401, 411