SIGNIFICANT X-RAY LINE EMISSION IN THE 5–6 keV BAND OF NGC 4051

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ABSTRACT

A Suzaku X-ray observation of NGC 4051 taken during 2005 November reveals line emission at 5.44 keV in the rest frame of the galaxy which does not have an obvious origin in known rest-frame atomic transitions. The improvement to the fit statistic when this line is accounted for establishes its reality at >99.9% confidence: we have also verified that the line is detected in the three X-ray Imaging Spectrometer units independently. Comparison between the data and Monte Carlo simulations shows that the probability of the line being a statistical fluctuation is \( p < 3.3 \times 10^{-4} \). Consideration of three independent line detections in Suzaku data taken at different epochs yields a probability \( p < 3 \times 10^{-11} \) and thus conclusively demonstrates that it cannot be a statistical fluctuation in the data. The new line and a strong component of Fe K\( \alpha \) emission from neutral material are prominent when the source flux is low, during 2005. Spectra from 2008 show evidence for a line consistent with having the same flux and energy as that observed during 2005, but inconsistent with having a constant equivalent width against the observed continuum. The stability of the line flux and energy suggests that it may not arise in transient hotspots, as has been suggested for similar lines in other sources, but could arise from a special location in the reprocessor, such as the inner edge of the accretion disk. Alternatively, the line energy may be explained by spallation of Fe into Cr, as discussed in a companion paper.

Key words: galaxies: active – galaxies: individual (NGC 4051) – galaxies: Seyfert – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

New X-ray data from high-throughput missions such as XMM-Newton and Suzaku, along with the high spectral resolution afforded by the Chandra High Energy Transmission Grating (HETG) has led to the discovery of several important spectral signatures in active galactic nuclei (AGNs) that were not detectable using previous missions.

A joint XMM-Newton/Chandra observation of NGC 3516 (Turner et al. 2002) revealed the first detection of narrow line emission at 5.6 and 6.2 keV (the latter was able to be resolved from the strong Fe K\( \alpha \) line owing to the relatively high spectral resolution afforded by the HEG grating). While the line energies matched those expected for ionized species of Cr and Mn, the line strengths exceeded what might be expected from illumination of material with cosmic abundance ratios. One explanation considered was enhancement of Cr and Mn abundances from spallation of Fe. However, this was initially disfavored as the line ratios did not agree well with those predicted by Skibo (1997) for spallation of disk gas (Turner et al. 2002). The alternative possibility, of Doppler-shifted components of Fe emission, led to a suggestion of emitting hotspots on the accretion disk surface—with an expectation of observable shifts in line flux and energy as the hotspot traverses its orbit. Further examples of the phenomenon, dubbed “transient Fe lines,” soon came from observations of other AGNs, with many lines reported in the 5–6 keV regime (e.g., Yaqoob et al. 2003; Turner et al. 2004).

In this paper, we report the highly significant detection of an emission line at 5.44 keV in the rest frame of the nearby narrow line Seyfert 1 type AGN NGC 4051. The systemic redshift of the host galaxy is \( z = 0.0023 \) that yields a distance 9.3 Mpc for \( H_0 = 74 \text{ km s}^{-1} \text{ Mpc}^{-1} \) assuming the redshift to arise from the Hubble flow. However, for such nearby galaxies a more reliable estimation of distance can be obtained from use of the Tully–Fisher relation, giving a distance of 15.2 Mpc (Russell 2004) in this case, which we adopt in this paper.

NGC 4051 was observed by Suzaku in 2005 and 2008. The 2005 observations have previously been described and analyzed by Terashima et al. (2009), who showed that the X-ray source was highly variable on short timescales, and that a spectral model including variable partial-covering absorption was required to fit the data. Here, we make a joint analysis of the 2005 observation together with the new 2008 data in which we concentrate specifically on the detection of the narrow emission line and its variability. We then discuss the possible origin of the line in the context of several popular models.

2. OBSERVATIONS

The Suzaku X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) instrument comprises four X-ray telescopes (Mit-suda et al. 2007) each with a CCD in the focal plane. XIS CCDs 0,2,3 are configured to be front-illuminated (FI) and provide useful data over \( \sim 0.6–10.0 \text{ keV} \) with energy resolution FWHM \( \sim 150 \text{ eV} \) at 6 keV. XIS 1 is a back-illuminated CCD and has an enhanced soft-band response (down to 0.2 keV) but lower area at 6 keV than the FI CCDs as well as a larger background level at high energies, consequently this detector was not used in our analysis. Suzaku also carries a non-imaging, collimated hard
X-ray detector (HXD; Takahashi et al. 2007) whose PIN instrument provides useful data over 15–70 keV for bright AGNs.

Our analysis used all available Suzaku observations of NGC 4051 comprising data from 2005 November 10–13 (observation ID 700004010) and 2008 November 6–12 (703023010) and 23–25 (703023020) as summarized in Table 1. The data were reduced using v6.4.1 of HEASOFT and screened to exclude (1) periods during and within 500 s of the South Atlantic Anomaly (SAA), (2) with an Earth elevation angle less than 10°, and (3) with cut-off rigidity >6 GeV. The source was observed at the nominal central position for the XIS during 2008 and at the nominal central position for the HXD during 2005. The FI CCDs were in 3 × 3 and 5 × 5 edit modes, with normal clocking mode. For the XIS we selected events with grades 0, 2, 3, 4, and 6 and removed hot and flickering pixels using the SISCLEAN script. The spaced-row charge injection (SCI) was used. The XIS products were extracted from circular regions of 2.9′ radius with background spectra from a region of the same size, offset from the source (avoiding the calibration sources at the edges of the chips). The response and ancillary response files were created using xisrmfgen v2007 May and xismarfgen v2008 Mar.

NGC 4051 is too faint to be detected in the HXD Gadolinium Silicate instrument, but was detectable in the PIN. For the analysis we used the model “D” background (Fukazawa et al. 2009). As the PIN background rate is strongly variable around the orbit, we first selected source data to discard events within 500 s of an SAA passage, we also rejected events with day/night elevation angles >5°. The time filter resulting from the screening was then applied to the background events model file to give PIN model-background data for the same time intervals covered by the on-source data. As the background events file was generated using 10 times the actual background count rate, an adjustment to the background spectrum was applied to account for this factor. hxdtdcor v2007 May was run to apply the deadtime correction to the source spectrum. To take into account the cosmic X-ray background (Boltdt & Leiter 1987; Gruber et al. 1999) xspec v11.3.2ag was used to generate a spectrum from a CXB model (Gruber et al. 1999) normalized to the 34′ × 34′ Suzaku PIN field of view, and combined with the PIN instrument background file to create a total background file. The mean exposure times for XIS are given in Table 1. The exposure times for the PIN were 112, 204, and 59 ks for 2005 November 10, 2008 November 6, and 2008 November 23, respectively.

Spectral fits used data from XIS 0, 2, and 3, for the 2005 data. As use of XIS2 was discontinued after a charge leak was discovered in 2006 November, the 2008 analysis used only XIS 0 and 3. In this paper, XIS data were fit over 3.0–10 keV, PIN data were fit simultaneously with the XIS, in the range 15–50 keV. In the spectral analysis, the PIN model flux was increased by a factor of 1.16 for 2008 data and 1.18 for 2005 data, which are the appropriate adjustments for the instrument cross-calibration at those epochs of the observation. XIS data were binned at the HWHM instrumental resolution while PIN data were binned to be a minimum of 5σ above the background level for the spectral fitting.

### 3. SPECTRAL FITTING

The mean Suzaku count rate over 0.5–10 keV during the low state of 2005 was 0.45 XIS count s⁻¹ per FI XIS and 0.04 PIN count s⁻¹. During the high-state of 2008 November 6 it was 2.06 XIS count s⁻¹ per FI XIS and 0.07 PIN count s⁻¹ (Table 1). The count rates recorded correspond to an observed 2–10 keV flux range (0.87–2.42) × 10⁻¹¹ erg cm⁻² s⁻¹ and a 10–50 keV flux range (2.44–3.63) × 10⁻¹¹ erg cm⁻² s⁻¹. The 2005 data represent a historically low state, as noted by Terashima et al. (2009) and during 2008 the source was close to the historical average flux level. The 2008 November 6 Suzaku observation was accompanied by a contemporaneous HETG exposure that reveals a wealth of emission and absorption features from several zones of ionized gas. The HETG analysis will be described in detail in another paper (A. Lobban et al. 2010, in preparation).

#### 3.1. Fitting the PCA Offset Component

To assist in modeling the full-band Suzaku data, we first performed a decomposition of the events from all three Suzaku observations using principal components analysis (PCA) using the SVD method and code of Miller et al. (2007). A full description of the PCA decomposition of these data is reported by Miller et al. (2010). In summary, PCA is a mathematical decomposition of the data into orthogonal “eigenvectors.” The dominant variations are ascribed to eigenvectors of the lowest orders. In the case of NGC 4051 the data were found to be well described by a steady “offset” component having a hard spectrum (Figure 1 and see Miller et al. 2010) while the first-order variable component, eigenvector 1, is consistent with an absorbed power law of constant slope whose variations in intensity dominate the spectral variability of the source (consistent with the analysis of Terashima et al. 2009). The physical origin of the offset component is of great interest. The low-state spectrum of NGC 4051 is composed of this component plus some contribution by eigenvector 1. Fitting the lowest flux subset of the 2005 data, Terashima et al. (2009) found the hard component to be best described using a partially covered reflection component. Our analysis of the PCA offset component provides another way to probe the lowest flux levels of the source and, while we find an acceptable fit using a combination of reflection (modeled using pexrav) plus a contribution from the powerlaw continuum (Γ = 2.3, fixed from fitting eigenvector 1), both emission components require absorption by a complex of ionized gas. Fortunately the multiple layers of ionized gas can be well constrained using HETG and LETG data (Collinge et al. 2001; Steenbrugge et al. 2009; A. Lobban et al. 2010, in preparation), reducing the degeneracy of the Suzaku fit. In addition to these components, Fe Kα line
emission is evident in the offset spectrum at a fitted energy \( E = 6.398 \pm 0.023 \) keV having a width \( \sigma = 0.045^{+0.037}_{-0.045} \) keV and flux \( n = (1.90 \pm 0.26) \times 10^{-5} \) photons cm\(^{-2}\) s\(^{-1}\). (Throughout this paper, errors are quoted at 90% confidence for the appropriate number of interesting parameters in the fit.) The resulting fit statistic was \( \chi^2 = 130/153 \) d.o.f.

Intriguingly, the normalization of the reflection continuum is extremely high relative to that of the primary continuum. The inconsistency of reflection and continuum strengths may indicate that the partial-covering absorption comprises a larger part of this component than currently modeled. The relatively high flux of the hard component was also noted by Terashima et al. (2009) based upon fitting the 2005 data and is fully explored by A. Lobban et al. (2010, in preparation).

In addition to the prominent narrow Fe Kα line, a strong excess of line emission is evident in the PCA offset spectrum, at 5.44 keV (Figure 1). No significant residuals appear in eigenvector 1 at that energy (Miller et al. 2010). The new line is thus consistent with having an origin associated with the hard offset component and neutral component of Fe Kα emission.

3.2. Fitting the 2008 Contemporaneous Chandra and Suzaku Data

As the 2008 November 6 epoch provides contemporaneous HEG data for the Suzaku observation, we fit those spectra together over 3–8 keV, combining the superior energy resolution of HEG and the good statistical quality of the FI XIS units (0.3) to obtain the best possible constraints on the width and energy of the neutral component of Fe Kα. A joint fit to those data using a simple power-law plus single Gaussian line showed residual excesses in the 5–6 keV band in Suzaku XIS data (Figure 2).

We refit, adding to the model a single component of absorption, a Gaussian representation of the Kβ line fixed at a rest energy of 7.05 keV with a flux linked to be 13.5% of the Kα component (e.g., Leahy & Creighton 1993; Palmeri et al. 2003), a narrow absorption line detected at an observed energy of 7.1 keV (as discovered by Pounds et al. 2004 and confirmed by Terashima et al. 2009) plus a component to model the narrow line emission evident at 6.62 keV in HEG data (A. Lobban et al. 2010, in preparation). The fit yielded a line energy \( E = 6.410 \pm 0.015 \) keV, width \( \sigma = 50^{+33}_{-23} \) eV, and normalization \( n = (1.90 \pm 0.395) \times 10^{-5} \) photons cm\(^{-2}\) s\(^{-1}\). The equivalent width (EW) for the Fe Kα line component is 95 eV against the total continuum level observed during 2008. The constraint on the width of the Fe Kα line is equivalent to a FWHM velocity broadening of \( 5540^{+2846}_{-3664} \) km s\(^{-1}\) (90% confidence interval). Assuming the true line centroid energy to be 6.40 keV, the 90% confidence constraint on energy from the combined HEG/XIS data limits the bulk velocity of this emitter to \( 250 \) km s\(^{-1} \gtrsim v \gtrsim -1200 \) km s\(^{-1}\) where negative velocity denotes outflow.

As the PCA decomposition indicates the presence of a weak broad component of Fe Kα on eigenvector 1 (Miller et al. 2010), we tried adding a second component of Fe Kα emission to the model, with the energies of both line components linked. This addition improved the fit statistic by \( \Delta \chi^2 = 5 \), giving the same line energy as for the single component model, with \( \sigma_1 = 1^{+23}_{-1} \) eV and normalization \( n_1 = (1.12 \pm 0.32) \times 10^{-5} \) photons cm\(^{-2}\) s\(^{-1}\) (EW = 41 eV), \( \sigma_2 = 145^{+70}_{-52} \) eV and normalization \( n_2 = (1.07 \pm 0.45) \times 10^{-5} \) photons cm\(^{-2}\) s\(^{-1}\) (EW = 43 eV). Although the two-component parameterization of Fe Kα offers only a marginal improvement to the fit, it is of interest with regard to consistency with the PCA decomposition, which indicates the weak broad component of Fe Kα emission to be present on eigenvector 1.

In subsequent fits we fix the Fe Kα model line width at \( \sigma = 50 \) eV obtained from the simple fit, while bearing in mind the possible more complex solution for the line profile. As the

Figure 1. Offset component from the PCA decomposition of all of the 2005 and 2008 Suzaku XISO + 3 and PIN data. A strong narrow Fe Kα line is evident at 6.4 keV, along with emission at 5.4 and, more weakly, at 6 keV. (A color version of this figure is available in the online journal.)

Figure 2. Suzaku XISO + 3 data and residuals from the mean 2008 November 6 spectrum, compared to an absorbed power law plus Gaussian line at 6.4 keV.
PCA is consistent with a common origin for Fe Kα emission and the line at 5.44 keV, and as the widths of the two lines are consistent (and as there is no other useful constraint available for the indeterminate line width) hereafter we fixed both to $\sigma = 50$ eV in spectral fitting.

3.3. Fitting the 2005 Suzaku Data

To assess the significance of the line at 5.44 keV we returned to direct fitting of the 2005 data, where the source was observed to be at a low flux and where PCA indicates that the line would have the highest EW. We fit the summed 2005 data from the FI XIS units 0, 2, and 3 using an absorbed continuum model, applying it to the 3–10 keV band for the purpose of examining the data for features of interest. A Gaussian line was included in the fit, to account for the Fe Kα emission, fixed at the energy and width found using HEG/XIS. As evident in Figure 3 the mean spectrum from 2005 data shows an excess of counts at 5.44 keV with additional structure evident around 6 keV. We performed a more complex fit to properly assess the line strengths and significance. We added to the model a Gaussian representation of the Fe Kβ line fixed at a rest energy of 7.05 keV with a flux linked to be 13.5% of the Kα component. The model also included the narrow absorption line detected at an observed energy of 7.1 keV as discovered by Pounds et al. (2004) and confirmed by Terashima et al. (2009), plus a component to model the narrow line emission evident at 6.62 keV (A. Lobban et al. 2010, in preparation). The fit yielded $\chi^2 = 176/101$ d.o.f. and the strongest unmodeled feature remains evident as an excess of counts at 5.44 keV.

Addition of a Gaussian line ($\sigma = 50$ eV) reduced the fit statistic by $\Delta\chi^2 = 32$, yielding $E = 5.44 \pm 0.03$ keV, flux $n = 5.03^{+2.02}_{-2.01} \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ and EW 46 $\pm$ 16 eV. Addition of a second line of the same width yielded a further improvement $\Delta\chi^2 = 34$, $E = 5.95 \pm 0.05$ keV, line flux $n = 5.05^{+2.05}_{-1.95} \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$, with an EW of 44$^{+17}_{-16}$ eV and a final fit statistic $\chi^2 = 117/97$ d.o.f. In this fit the flux and EW of the Fe Kα line were $n = (1.59 \pm 0.23) \times 10^{-3}$ and 195 $\pm$ 24 eV, respectively.

To further examine the source behavior at low flux levels we isolated the lowest flux subset of the 2005 data using an intensity filter based upon the 0.5–10 keV band count rate, taking data below a threshold of 0.47 ct s$^{-1}$ (per FI XIS). The intensity cut effectively removed the periods of source flaring from consideration. This filtering thus resulted in a very-low-state spectrum that had a mean 2–10 keV flux 6.1 $\times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. Again, fitting a simple absorbed continuum model over 3–10 keV leaves two strong positive residual features between 5 and 6 keV (Figure 4) confirming the prominence of the 5.44 keV line at low flux levels and indicating the possible presence of emission at 5.95 keV.

3.4. The Full Model

To assess the full properties of the source and investigate the robustness of the line detections to the continuum model used, we then fit over 0.75–50 keV (the full band of the Suzaku data). We simultaneously fit spectra from the three Suzaku observations. The 2008 HETG exposure (that overlapped the 2008 November 6 Suzaku observation) shows a wealth of absorption and emission lines that can be modeled using three zones of ionized gas (A. Lobban et al. 2010, in preparation): those soft-band absorbers were fixed in the Suzaku fit, after which two additional gas layers were required to accurately model the source across the full Suzaku bandpass. The fit also included an Fe Kα emission line fixed at a width of $\sigma = 50$ eV as before. Finally, an absorbed ionized reflector was included to account for the curvature in the soft band. The full model is detailed in Table 2 and the fit is illustrated in Figure 5.
The marked spectral variability observed (Figure 5) can be accounted for by allowing variations in the covering fraction of one absorbing layer (having $N_H \sim 10^{23} \text{ cm}^{-2}$, $\log \xi \sim 0.18$), a solution that is similar to other well-studied AGNs of this class (e.g., Pounds et al. 2004; Risaliti et al. 2007; Miller et al. 2008; Turner et al. 2008). This fit yielded $\chi^2 = 947/547$ d.o.f. with the overall curvature modeled well across all epochs and the residual $\chi^2$ contributed mainly by some unmodeled spectral features. The addition of a line ($\sigma = 50$ eV) constrained to lie in the range 3–8 keV yielded a detection at 5.44±0.03 keV and improved the fit statistic by $\Delta \chi^2 = 20$; addition of another line under the same constraints gave 5.98±0.05 keV and $\Delta \chi^2 = 9$ improvement to the fit. We conclude that the high significance for the detection of the 5.44 keV line is robust to the continuum used, while the significance of the detection of a line at 5.95 keV is sensitive to the continuum form assumed.

3.5. A Critical Examination of the Reality of the Lines

Before proceeding any further with the modeling, we performed several checks to be assured that the new line is attributable to the AGN and is significant. First, to confirm that the line is not an artifact of poor background subtraction, we examined the background spectrum and calibration source data. First, we note that the background comprises just 2.5% of the total count rate in the 5–7 keV band for the XIS spectral data when the source is at its lowest flux level, during 2005 and 1.3% when the source is brighter, during 2008. Regarding the line at 5.44 keV, we found there to be no line emission evident at that energy in the background spectrum. Fitting the background spectra from the three Suzaku observations we obtained an upper limit (90% confidence) for the flux of a line at 5.44 keV in the background spectrum $n < 4.14 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$, i.e., <1% of the detected line flux.

The lack of a feature at comparable flux or EW in the background data also rules out an origin of the 5.44 keV line as a detector feature. We then examined each XIS independently, and found the 5.44 keV line to be significantly detected in each XIS unit independently, further verifying the reality of the reported feature (Figure 6).

Regarding the more tentative line at 5.95 keV: the XIS chip does include a Mn calibration source emitting a line at 5.9 keV for the purpose of calibration of the XIS energy scale. The Mn contamination is at a level 10% of the measured line strength in the AGN spectrum. As the source extraction cell is further from the Mn calibration source than the background cell and therefore subject to less contamination, we estimate the Mn line contamination from any source and background extraction cells for scientific counts from that source are obviously conservatively excluded. The calibration source is located at the chip edge and the chip does include a Mn calibration source emitting a line at 5.9 keV.

The Spectral Model

| Parameter | 2005   | 2008a  | 2008b  |
|-----------|--------|--------|--------|
| $\Gamma$  | 2.47   | ±0.02  |        |
| $PL_{\text{norm}}$ | 0.58  | ±0.01  | 1.818  | ±0.004 | 1.283  | ±0.005 |
| $N_{\text{HI}}$ |        |        |        |
| $N_{\text{HI}}^a$ |        |        |        |
| $\log \xi$ | 3.40   | ±0.03  |        |
| $N_{\text{HI}}^b$ | 1.17   | ±0.04  |        |
| $\log \xi_5$ | 0.18$^{+0.15}_{-0.16}$ |        |        |
| Covering($N_{\text{HI}}$) | 71     | ±2%    | 35     | ±2%    | 38     | ±2%    |
| $P_{\text{exa}}^a$ | 0.40   | ±0.03  |        |
| $P_{\text{exa}}^b$ | 3.84   | ±0.19  | 5.41   | ±0.26  | 4.84   | ±0.28  |
| $N_{\text{HI}}^c$ | 50.0$^{+5.0}_{-5.0}$ |        |        |
| $\log \xi_6$ | 2.62   | ±0.05  |        |
| $\log \text{Refion}^d$ | 2.94   | ±0.07  |        |
| $\text{Refion}_{\text{norm}}$ | 1.03   | ×10$^{-2}$ |        |

Notes. $^a$ per limit (90% confidence) for the flux of a line at 5.44 keV in the background spectrum. Fitting the background data also rules out an origin of the 5.44 keV line as a detector feature. We then examined each XIS independently, and found the 5.44 keV line to be significantly detected in each XIS unit independently, further verifying the reality of the reported feature (Figure 6).

The calibration source is located at the chip edge and the chip does include a Mn calibration source emitting a line at 5.9 keV for the purpose of calibration of the XIS energy scale. The calibration source is located at the chip edge and the counts from that source are obviously conservatively excluded from any source and background extraction cells for scientific analysis. However, we do detect a weak Mn Kα emission in the background spectrum. The Mn contamination is at a level <10% of the measured line strength in the AGN spectrum. As the source extraction cell is further from the Mn calibration source than the background cell and therefore subject to less contamination, we estimate the Mn line contamination from the calibration source to be <10% for the 2005 spectrum. In spectral fitting, the greatest concern for the Mn line is the possible contamination by the weak broadened Fe Kα emission evident in the fit to eigenvector 1 (Miller et al. 2010) which may lead to the strength of the Mn line being over-estimated from simple fits. Because of the various issues associated with a clean measurement of any line at 5.95 keV and the sensitivity to the continuum form assumed we concentrate only on the strong line detection at 5.44 keV.

To confirm the significance of the line we performed Monte Carlo simulations using the method described in Porquet et al. (2004) and in Markowitz et al. (2006). We took the null
hypothesis to be that the spectrum is simply an absorbed power-law continuum with parameters derived from fitting the broadband data but allowing for the statistical uncertainty on the continuum parameters and including the narrow Fe Kα line whose presence is well established in this source (A. Lobban et al. 2010, in preparation). We used the \texttt{xspec} command \texttt{fakeit} to create 3000 fake \textit{Suzaku} spectra with photon statistics expected from the 2005 exposure, assuming the same instruments to be operational as for the actual observation. The simulated data were grouped to the HWHM energy resolution of the instruments, the same as the observational data. Following the procedure used to test the real data for the presence of a narrow line, we fitted each fake spectrum to obtain the values of $\Delta \chi^2$ obtained from statistical fluctuations in the data. To map the distribution of $\Delta \chi^2$ across the simulated spectra, each simulated spectrum was fitted over the 3–10 keV energy range, stepping through using energy bins whose centers were increased in increments of 100 eV. The line energy was allowed to be free within each energy bin tested and the value of $\Delta \chi^2$ was recorded at each point in the spectrum. This method makes no assumptions about the energy at which a line might be detected and over the course of the testing, all energies are tested for the presence of a line. When we fit the simulated data we are testing whether we can produce, from statistical fluctuations, a contribution to $\chi^2$ at the same or greater level as found in the actual data at any energy in the range of interest. The fits to the simulated data yield a distribution of $\Delta \chi^2$ for comparison with the actual data. We found the most extreme statistical fluctuation to yield a $\Delta \chi^2$ contribution of 19.3 in the 3–10 keV band in the set of simulated data (i.e., in 3000 simulations no false line appears at any energy contributing $\Delta \chi^2 = 32$ as found in 2005 data). Thus, the probability of satisfying the null hypothesis is $p < 3.3 \times 10^{-4}$ for the line found at 5.44 keV.

### 3.6. Application of a Disk Hotspot Model

As an alternative to modeling using individual Gaussian lines, we fitted the data using a single disk line from a narrow annulus, such that the red horn of such a line might explain the peak at 5.44 keV. We assumed the system to contain a non-rotating black hole, that the line is Fe Kα emission from neutral material (at 6.4 keV), that the emissivity pattern across the disk can be described by $r^{-q}$ where the emissivity index $q = -2.5$ and that the hotspot exists over a narrow annulus of width $\Delta r = 1 r_g$. We used the same baseline model as for testing the Gaussian lines (Section 3.3).

To fit the 5.44 keV peak as the red Doppler horn of a disk line requires an emitting radius (21$^{\pm3}$)$r_g$ (where $r_g = GM_{BH}/c^2$ denotes gravitational radii) in a low inclination system with 27$^{\pm1}$° with $\chi^2 = 128/95$ d.o.f.; the corresponding blue horn is then predicted to lie at 6.62 keV and the data are consistent with that model. While there is evidence for line emission in the 6.5–7 keV regime, such lines are commonly observed as emission from ionized species of Fe, and thus the identification of emission blueward of 6.4 keV is currently ambiguous.

### 3.7. Examination of the Line Variability

Fits to the mean spectra from each observation have shown consistent line fluxes for Fe Kα and the line at 5.44 keV and these show an EW that appears to have changed as the source flux varied. Figure 7 shows the ratio of data in the Fe Kα regime to a common local continuum fit; the fact that the source spectrum is steeper at high flux is reflected in the systematics of the residuals. To confirm the significance of the change in EW we fit the 2008 data with a model that fixed the line equivalent width for the feature at 5.44 keV to that found during 2005; after refitting this resulted in a worse fit with $\Delta \chi^2 = 142$. Alternatively, fixing the flux of the new lines at the 2005 values and refitting, we found...
\( \Delta \chi^2 = 0 \), indicating that the line fluxes may be consistent with lines of constant flux across the data.

As the limits on line flux provide the potential to distinguish between models, we tested all available high-quality data in a self-consistent manner. Taking the model from Section 3.3 we fixed the line energy and width to specifically test the constancy of the 5.44 keV line. In addition to testing the mean spectrum from each Suzaku observation, we sub-divided the 2005 and 2008 exposures to sample the line more finely in flux. For 2005 an intensity selection was made on the 0.5–10 keV count rate <2.0 ct s\(^{-1}\) per XIS as before. For 2008 intensity selections were made >3.0 ct s\(^{-1}\) per XIS (i1), 2.0–3.0 ct s\(^{-1}\) per XIS (i2) and >5.0 ct s\(^{-1}\) per XIS (i3). The results are shown in Table 3 where both the fits for each observation are tabulated, as well as the intensity-selected results. As noted previously, the line is required at a high level of confidence in the 2008 November data (which is more sensitive to the features than the November 23 data, owing to the long exposure and high flux state of the source).

Table 3 shows line flux along with improvements in the fit statistic and EW for each fit. Note that the mean observation fits in Table 3 show slightly tighter constraints in line flux for 2005 compared to the values noted in Section 3.3 because the initial fits to 2005 data had the line energy left free. The data are consistent with the 5.44 keV line existing at the same flux level throughout the Suzaku observations considered in Table 3 and the high significance of the line detection across several time slices of data provides compelling evidence for the reality of the line; conclusively ruling out the possibility of the line detection being a statistical fluctuation in the spectral data. Considering the three independent Suzaku detections of the line, as shown in Table 3 Suzaku observations 1, 2, and 3 yield improvements to the fit \( \Delta \chi^2 = 32, 19, 19 \), respectively, and a probability of all three detections being false is \( p \approx 3 \times 10^{-11} \).

We repeated the fits with the line energy allowed to be free and found the fitted energy to be consistent with 5.44 keV and that the line flux had not been significantly affected by freezing the energy.

To extend the test for line flux variations we reduced and fit the XMM-Newton spectra obtained during 2001 and 2002. We followed the standard reduction method for the pn data, as detailed by Ponti et al. (2006) and found the data to be consistent with the presence of a line at the same flux as found using Suzaku. An independent analysis of the XMM data by de Marco et al. (2009) reported the presence of an excess of counts in the 5.4–6.2 keV band for NGC 4051, compared to their parameterization of the local continuum. Examination of the XMM data shows an excess of emission at ~6 keV in the XMM spectra and so tentatively supports the possibility of that additional energy-shifted line in this source.

BeppoSAX also observed NGC 4051, finding the source to be in a very low flux state during 1998 as reported by Guainazzi et al. (1998). We extracted and fit the archived BeppoSAX Medium Energy Concentrator spectrum from units 2 and 3 (combined) and tested for the presence of the line. However, the data yielded only a loose upper limit of \( 4 \times 10^{-5} \) photons cm\(^{-2}\) s\(^{-1}\) for a line at 5.44 keV. Given the poor constraint obtained we do not consider those data any further.

Combining the results from Suzaku and XMM observations (specifically, Table 3 lines 1, 2, 4, 5, 7–9, and 10) and comparing the data to a constant model yields \( \chi^2 = 4.7/7 \) d.o.f. Further to this test, we split the data by time instead of intensity and repeated the test, reaching the same conclusion, i.e., that the data are consistent with a line of constant flux over a timescale of several years and over large changes in observed continuum flux. The limits on measured line fluxes mean we can rule out line variability greater than a factor of ~2 in the line flux sampled on these timescales, across the baseline time period considered.

### 4. DISCUSSION

While numerous claims exist in the literature for emission lines at unexpected energies (see Turner & Miller 2009, for a review), the reality of the lines has been questioned by some. Vaughan & Uttley (2008) considered 38 published results on transient emission and absorption lines reported in the literature: those authors find a linear relationship between the fitted feature strength and its uncertainty. Vaughan & Uttley (2008) noted that observations with more signal apparently reveal weak lines but do not show tightly constrained strong lines which should sometimes also show up by chance. The conclusion of the Vaughan & Uttley (2008) literature review was that there is
a publication bias in reporting of these results, and that many of the reported detections are merely statistical fluctuations. This question has now been addressed with two systematic analyses of samples of AGNs. Tombesi et al. (2010) present a study of the occurrence and reality of energy-shifted absorption lines in a sample of AGNs finding a deviation from the linear relationship of line EW and uncertainty found by Vaughan & Uttley (2008) in the sense that their distribution showed more significant detections of lines in sources studied. Tombesi et al. (2010) compare their absorption line measurements with those of the Fe Kα emission in the same sources and show that these two sets of measurements follow the same distribution.

Another recent energy-shifted lines: such a bias may explain at least some of the fluctuations and that the absence of well-constrained detections of strong features in the Vaughan & Uttley (2008) analysis may be due in part to a limit on the ability of current X-ray instruments to detect such lines. It also would appear likely that long observations of bright sources may not have been proposed or approved early in the XMM and Suzaku missions and so the sample of observations completed to date is likely biased against those that would have shown tightly constrained energy-shifted lines: such a bias may explain at least some of the effect discussed by Vaughan & Uttley (2008). Another recent study by de Marco et al. (2009) undertook a systematic analysis of a sample of bright Seyfert 1 galaxies and confirmed many of the individual detections of energy-shifted emission lines claimed in the literature, supporting the general reality of the phenomenon by consideration of the statistics of the sample results as a whole. With conflicting views in the literature it is clear that the detection of significant new examples of the energy-shifted line phenomenon is very important at this time.

4.1. Hard X-ray Line Emission in NGC 4051

NGC 4051 can be modeled using a power-law continuum covered by multiple zones of gas, several in the column density range $10^{23}$–$10^{24}$ cm$^{-2}$, that impart emission and absorption features to the X-ray spectrum. The marked spectral variability with observed flux can be explained by changes in covering of the power-law continuum by one of the high-column absorbers, as found for other similar AGNs (e.g., Pounds et al. 2004; Risaliti et al. 2007; Miller et al. 2008; Turner et al. 2008). Significant line emission has been observed at 5.44 keV in the 2005 Suzaku observation of NGC 4051. Comparison of low- and high-state X-ray data for NGC 4051 shows that the newly discovered line appears prominent in the low-flux state along with the narrow component of Fe Kα emission from neutral gas, as expected if the observed low state is simply those times when a relatively large fraction of the continuum is suppressed by absorption.

The most recent measurements indicate NGC 4051 to have a black hole mass $M_{MBH} = 1.73^{+0.55}_{-0.52} 	imes 10^8 M_\odot$ and a radius for the Hβ broad line region (BLR) $R_{BLR} = 1.87^{+0.54}_{-0.50}$ light days (Denney et al. 2009). The Hβ FWHM in the rms spectrum of Denney et al. is 1034 ± 41 km s$^{-1}$ (although those authors used the velocity dispersion rather than the FWHM in their mass estimate). If we assume the same geometrical correction factor between line width and circular velocity as those authors to scale the respective FWHM measurements, the line width of Fe Kα is indicative of an origin at $r \approx 1.87(1034/5540)^2 \approx 0.065$ light days, or $2 \times 10^{14}$ cm, with a 90% confidence range $8.6 \times 10^{12}$–$1.7 \times 10^{15}$ cm. As we have scaled to the optical reverberation results, this radius estimate is secure provided the X-ray and optical line-emitting regions have similar structure and orientation with respect to the observer, but the large uncertainty is dominated by the uncertainty in the line width measurement. Further to the measurement error is the uncertainty as to whether, as suggested by the form of eigenvector 1, the Fe Kα emission has both broad and narrow components, in which case we would have to conclude that we are seeing contributions from regions both within and outside of the region noted above. Given the limited signal-to-noise in the regime of Fe Kα in the HEG data this question remains open with current data.

In the single component model for Fe Kα emission, spectral fitting to the HEG plus Suzaku data yields an Fe Kα emission line of flux $n = (1.90 \pm 0.40) \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$. The strength of the Fe Kα line emission, normalized to the illuminating continuum, can be used to set limits on the reprocessing gas in which it arises. Following Yaqoob et al. (2010) and correcting for the continuum slope found here, we estimate an efficiency for the production of line photons (defined as the ratio of line flux to incident flux above the ionization edge) to be $x_{FeK} \sim 0.018$. The line measured here sets a lower limit on the column density of the emitting region $N_H > 10^{24}$ cm$^{-2}$ and in the toroidal reprocessor model suggests a global covering factor of $\sim 0.9$ with an approximately face-on view down the pole of the structure. As it is difficult to determine the intrinsic continuum strength from the observed continuum the interpretation of these data in the context of the toroidal model is subject to some uncertainty that in turn, leaves the derived global covering factor uncertain by a factor of a few.

Combining the minimum column density of the line-of-sight gas with the radial constraints and knowledge of the gas having a high covering fraction yields a mass estimate $\gtrsim 4 \times 10^{-7}$ $M_\odot$ for the gas emitting the Fe Kα line, assuming the nominal radius of emission of $2 \times 10^{14}$ cm. The 90% confidence uncertainty in the distance translates into a confidence region on the mass lower limit of $5 \times 10^{-8}$–$0.1$ $M_\odot$. If a torus is not the true geometry of the gas then, of course, the covering factor could be different to this value. Further to the uncertainties mentioned, the line may be comprised of contributions from two regions. Taking instead the two-component fit to the Fe Kα profile then the column and/or global covering requirements are reduced for each of the two emitting regions.

The PCA decomposition (Miller et al. 2010) suggests a link between the origin of the Fe Kα line and that of the line at 5.44 keV. Observation of similar lines in other AGNs has motivated discussion of several possible origins, including spallation and hotspot emission from the accretion disk.

The solution found in the context of the disk hotspot model suggests that the emitting radius is between 18 and 24 $r_s$. The orbital timescales at these radii are ~4–6 ks for 18–24 $r_s$ for the black hole mass considered here. The observation of a steady line flux over 2005–2008 provides a constraint on the disk hotspot hypothesis as the three year baseline is equivalent to ~16,000–24,000 orbits about the black hole over the radial range of interest (and tens of orbits just considering the line persistence within the 2005 observation). Theoretical modeling indicates that hotspot events are not expected to last longer than a few orbital timescales at these small radii (Karas 2001) and that a given hotspot would suffer measurable flux and energy changes as the material spirals in (Dovciak et al. 2004). However, persistent steady lines could arise from a special radius in the disk or other rotating reprocessor without any constraining expectation of flux or energy variability. If the special radius is interpreted as the truncation radius of the inner
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