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THE SPIN OF THE SUPERMASSIVE BLACK HOLE IN NGC 3783

L. W. BRENNEMAN1, C. S. REYNOLDS2,3, M. A. NOWAK4, R. C. REIS5, M. TRIPPE2, A. C. FABIAN5, K. IWASAWA6, J. C. LEE7, J. M. MILLER8, R. F. MUSCHOTZKY2,3, K. NÁNDRA9, and M. VOLONTERI8

1 Harvard-Smithsonian CFA, 60 Garden Street MS-67, Cambridge, MA 02138, USA
2 Department of Astronomy, University of Maryland, College Park, MD 20742, USA
3 Joint Space Science Institute (JSSI), University of Maryland, College Park, MD 20742, USA
4 Institute of Astronomy, University of Cambridge, Madingley Rd., Cambridge CB3 0HA, UK
5 ICREA and Institut de Ciències del Cosmos (ICC), Universitat de Barcelona (IEEC-UB), Martí i Franquès, 1, 08028 Barcelona, Spain
6 INAF and Istituto Nazionale di Astrofisica, Rome, Italy
7 Department of Astronomy, Harvard University, Harvard-Smithsonian CFA, 60 Garden Street MS-6, Cambridge, MA 02138, USA
8 Department of Astronomy, University of Michigan, Ann Arbor, MI 48109, USA
9 Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse 1, 85740 Garching, Germany

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ABSTRACT

The Suzaku AGN Spin Survey is designed to determine the supermassive black hole spin in six nearby active galactic nuclei (AGNs) via deep Suzaku stares, thereby giving us our first glimpse of the local black hole spin distribution. Here, we present an analysis of the first target to be studied under the auspices of this Key Project, the Seyfert galaxy NGC 3783. Despite complexity in the spectrum arising from a multi-component warm absorber, we detect and study relativistic reflection from the inner accretion disk. Assuming that the X-ray reflection is from the surface of a flat disk around a Kerr black hole, and that no X-ray reflection occurs within the general relativistic radius of marginal stability, we determine a lower limit on the black hole spin of $a \gtrsim 0.88$ (99% confidence). We examine the robustness of this result to the assumption of the analysis and present a brief discussion of spin-related selection biases that might affect flux-limited samples of AGNs.

Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: Seyfert – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Ever since the seminal work of Penrose (1969) and Blandford & Znajek (1977), it has been recognized that black hole spin may be an important source of energy in astrophysics. Of particular note is the role that black hole spin may play in relativistic jets such as those seen in radio-loud active galactic nuclei (AGNs)—the magnetic extraction of the rotational energy of a rapidly spinning black hole is the leading contender for the fundamental energy source of such jets. Indeed, it has been suggested that the spin of the central supermassive black hole (SMBH) is a crucial parameter in determining whether an AGN can form powerful jets (i.e., whether the source is radio-quiet or radio-loud; Wilson & Colbert 1995), although the accretion rate/mode must clearly have a role to play (Sikora et al. 2007).

However, the importance of black hole spin goes beyond its role as a possible power source. The spin distribution of the SMBH population (and its dependence on SMBH mass) encodes the black hole growth history (Moderski & Sikora 1996; Volonteri et al. 2005; Berti & Volonteri 2008). In essence, if local SMBHs have obtained most of their mass during prolonged prograde accretion events in a quasar phase of activity, or in major mergers with similar mass SMBHs, we would expect a population of rapidly rotating SMBHs ($a > 0.6$) due to the angular momentum accreted from the disks or transferred at merger (Rezzolla et al. 2008). Here, we define $a \equiv c J / GM^2$, where $J$ is the angular momentum of the black hole and $M$ is its mass. On the other hand, if mergers with much smaller SMBHs (Hughes & Blandford 2003) or randomly oriented accretion events of small packets of material (King & Pringle 2007) have been the dominant growth mechanism, most of the SMBHs would be spinning at a much more modest rate.

To date, the cleanest probe of strong gravitational physics around SMBHs, including the effects of black hole spin, comes from examining relativistically broadened spectral features that are emitted from the surface layers of the inner accretion disk in response to irradiation by the hard X-ray source (Reynolds & Nowak 2003; Miller 2007). These spectral features have been observed and well characterized in both AGNs (Tanaka et al. 1995; Fabian et al. 1995) and stellar-mass black hole systems (Miller et al. 2002; Reis et al. 2008). The strongest feature in this so-called reflection spectrum is the fluorescent Fe Kα line (rest-frame energy of 6.4 keV); in contrast to lines from other elements, its relative abundance, high energy, and fluorescent yield make Fe Kα visible above the typical power-law continuum seen commonly in black hole systems. Extreme Doppler effects and gravitational redshifts combine to give this line (and all other features in the reflection spectrum) a characteristic broadened and skewed profile (Fabian et al. 1989; Laor 1991). Modern high signal-to-noise (S/N) data sets from XMM-Newton and Suzaku, combined with the latest models of reflection from an ionized accretion disk (e.g., Ross & Fabian 2005) and variable-spin relativistic smearing models (e.g., Brenneman & Reynolds 2006; Dauser et al. 2010), are giving us our first glimpses at the spins of SMBHs. However, due to the high S/N required to characterize the subtle effects of SMBH spin, interesting spin constraints have only been determined for a small handful of AGNs at present (MCG–6–30–15, Brenneman & Reynolds 2006; Fairall 9, Schmoll et al. 2009; SWIFT J1217.4+5654, Miniutti et al. 2009; 1H0707–495, Zoghbi et al. 2010; Mrk 79, Gallo et al. 2011; Mrk 335 and NGC 7469, Patrick et al. 2011; see Table 2).

Under the auspices of the Suzaku Key Project program, we have initiated a series of deep quasi-continuous observations...
of bright, nearby AGNs with the purpose of characterizing relativistic disk features in the spectra and setting constraints on the SMBH spin (Suzaku AGN Spin Survey; PI: C. Reynolds). In this paper, we present results from the first object to be studied under this program, the Seyfert 1.5 galaxy NGC 3783 ($z = 0.00973$; Theureau et al. 1998). This object possesses a high-column density and multi-component warm absorber (WA) that has been studied well by every spectroscopic X-ray observatory, including a 900 ks campaign by Chandra using the High-Energy Transmission Grating Spectrometer (HETGS; Kaspi et al. 2002; Krongold et al. 2003; Netzer et al. 2003). We show that, despite the presence of this complex WA, reflection signatures from the inner accretion disk can be identified and characterized with sufficient accuracy to constrain SMBH spin. We conclude that the SMBH is rapidly spinning with $a > 0.93$ (90% confidence). This result is shown to be robust to the exclusion of the complex, soft region of the X-ray spectrum as well as to uncertainties in the X-ray Imaging Spectrometer (XIS)/PIN cross-normalization.

This paper is organized as follows. Section 2 discusses the Suzaku observation of NGC 3783 and the basic reduction of the data. Section 3 then presents our modeling of the 0.7–45 keV time-averaged spectrum of NGC 3783, including our newly derived constraints on the SMBH spin. Section 4 summarizes our conclusions on NGC 3783 and addresses the role of spin-dependent selection biases in AGN samples.

2. OBSERVATIONS AND DATA REDUCTION

NGC 3783 was observed by Suzaku quasi-continuously for the period 2009 July 10–15, with the source placed in the Hard X-ray Detector (HXD) nominal aim point. After eliminating Earth occultations, South Atlantic Anomaly passages, and other high background periods, the observation contains 210 ks of “good” on-source exposure. The XIS data (XIS 0, XIS 1, and XIS 3; XIS 2 has been inoperable since 2006 November) were reprocessed using the xispi script in accordance with the Suzaku ABC Guide along with the latest version of the CALDB (as of 2010 March 29). XIS spectra and light curves were then produced according to the procedure outlined in the ABC Guide. For the XIS spectra, we combined data from the front-illuminated (FI) detectors XIS 0+3 data using the addascaspec script in order to increase S/N. The XIS spectra, responses, and backgrounds were then rebinned to 512 spectral channels from the original 4096 in order to speed up spectral model fitting without compromising the resolution of the detectors. Finally, the XIS spectra were grouped to a minimum of 25 counts per bin in order to facilitate robust $\chi^2$ fitting. The merged, background-subtracted, time-averaged FI spectrum has a net count rate of $4.960 \pm 0.002$ counts s$^{-1}$ for a total of 1.04 x $10^6$ counts. The total number of 2–10 keV counts is $6.26 \times 10^5$. The total XIS 1 count rate is $3.043 \pm 0.004$ counts s$^{-1}$ for a total of $6.40 \times 10^5$ or $3.14 \times 10^5$ when restricting to 2–10 keV. For all of the fitting presented in this paper, we allow for a global flux cross-normalization error between the FI and XIS 1 spectra. The XIS 1/FI cross-normalization is allowed to be a free parameter and is found to be approximately 1.03.

The HXD/PIN instrument detected NGC 3783, though the GSO did not. Data from PIN were again reduced as per the Suzaku ABC Guide. For background subtraction, we used the “tuned” non-X-ray background (NXB) event file for 2009 July

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10 http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/

11 http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/watchout.html
that occur much more rapidly. Also noteworthy is that the amplitude of variability decreases as one considers higher-energy bands, suggesting “pivoting” of the spectrum about some energy above the Suzaku/PIN band. The detailed nature of this spectral variability will be the subject of another publication (R. C. Reis et al., in preparation). For the remainder of this paper, we examine the high S/N spectrum from the time-averaged data set. We restrict our energy range to 0.7–10 keV in the XIS data, ignoring energies below 0.7 keV and from 1.5 to 2.5 keV to avoid areas of significant deviation between the three detectors, i.e., regions of known calibration uncertainty.

3. ANALYSIS OF THE TIME-AVERAGED SUZAKU SPECTRUM

3.1. A First Look at the Hard-band Spectrum

It is instructive to begin by examining the hard-band (3.5–45 keV) XIS+PIN spectrum. A simple power-law fit to this band reveals significant spectral complexity (Figures 2(a) and (b)). A narrow Kα fluorescence line of cold iron (6.4 keV) dominates; structure redward of this line indicates a narrow Kα emission line at 6.4 keV, a narrow Fe Kα(xvi) line (modeled as a Gaussian line), and the Kα line of cold iron (likely corresponding to a blend of the Kβ line of cold iron and the Lyα line of Fe xxvi).

Guided by these identifications, we construct a heuristic model of the hard spectrum consisting of a power-law continuum, a narrow Fe xxvi emission line (modeled as a Gaussian line centerd at 6.97 keV with σ = 10 eV), reflection from distant, low-velocity, cold matter (described by the pexmon model) [12], and a relativistically broadened cold iron Kα line (described by the laor model; Laor 1991). This model produces an excellent fit to the data (χ²/ν = 573/544 (1.05)) with the following parameters: photon index Γ = 1.68^{+0.01}_{-0.01}, reflection fraction R = 0.87^{+0.02}_{-0.05}, emission line equivalent widths W_{Fe xxvi} = 28^{+4}_{-3} eV, W_{broad} = 263^{+25}_{-15} eV, inner edge of line emitting disk r_{in} = 3.0^{+0.1}_{-0.2} r_g, index of line emissivity across disk q = 3.3 ± 0.1, and disk inclination i < 9°. If we replace the pexmon model with a pexrav and three separate Gaussian lines for narrow Fe Kα (6.4 keV, σ = 0.015 keV), Fe Kβ (7.06 keV, σ = 0.015 keV), and Compton shoulder (6.25 keV, σ = 0.1 keV), their equivalent widths are W_{Kα} = 98^{+5}_{-6} eV, W_{Kβ} ≤ 8 eV, and W_{CS} = 22^{+8}_{-6} eV, respectively. We note that, in this fit, the intrinsic widths of the iron lines were taken from their Chandra/HETG values (Yaqoob et al. 2005). Substituting the individual Gaussian lines and pexrav component for the pexmon model results in a modest change in the global goodness of fit (Δχ²/Δν = −32/−3), likely owing to the free normalizations of the emission lines (they are set at fixed ratios within pexmon). No statistically significant change is seen in the other model parameters.

For illustrative purposes only, Figure 2(c) shows the residuals that remain when the broad iron line is removed from this spectral model, and the remaining model parameters are re-fit. An obvious broad line remains. However, there are two reasons why this cannot be interpreted as “the broad line profile” for this object. First, NGC 3783 has a well-known, high-column density WA that, while principally affecting the soft spectrum, can also introduce subtle spectral curvature up to 10 keV or more. Second, the broadened iron line is just the tip of the iceberg; in particular when the accretion disk is ionized, the rest of the reflection spectrum has a sub-dominant but significant contribution that must be considered. The statistically unlikely value of the disk inclination derived from the simple fit (i < 9°) is a signal of these issues. For these reasons, we are forced into global modeling of the full 0.7–45 keV spectrum.

3.2. Guidance from the Long Chandra/HETG Observation

It is well known that NGC 3783 possesses a high-column density WA (e.g., Reynolds 1997); this is the greatest complexity we face when modeling the X-ray spectrum of this source. For guidance, we turn to the long (900 ks) observation of NGC 3783 with the HETGS on Chandra. Extensive analyses of the HETG data have been published (Kaspi et al. 2002; Krongold et al. 2007; Gardiner et al. 2008).

Figure 2. Left panel: simple power-law fit to the 3.5–45 keV XIS+PIN spectrum. Middle panel: zoom-in on the 4–8 keV region of the simple power-law fit. Note the probable “Compton shoulder” on the immediate low-energy side of the strong 6.4 keV emission line. Right panel: residuals remaining when the broad iron line component is removed from a simple phenomenological fit to the 3.5–45 keV data (see Section 3.1). In all panels the black points correspond to XIS 0+3 data, the red to XIS 1 data, and the blue to PIN data. The green line represents a data-to-model ratio of unity.
of Galactic absorption (\(N_H\)) range in the MEG data and the 1–7.5 keV range in the HEG data. Then jointly analyzed these spectra, noticing the 0.5–7 keV range of 15 photons per spectral bin in order to validate the use of each of the HEG and the MEG. These were binned to a minimum of 15 photons per spectral bin in order to validate the use of each of the HEG and the MEG. We permitted the overall cross-normalization between these four spectra to be free parameters; in all cases, the best-fitting cross-normalization is within 5% of unity.

Fitting these data with a power law modified by the effects of Galactic absorption (\(N_H = 9.91 \times 10^{20} \ cm^{-2}\); described using the \textsc{phaabs} model of \textsc{XSPEC}) results in a very poor fit with \(\chi^2/\nu = 58962/13112\) (4.50). The residuals suggest a soft excess component, soft X-ray absorption by a W A, and a prominent fluorescent iron K\(\alpha\) line at 6.4 keV. The effect of the WA is modeled using the \textsc{XSTAR} code (Kallman & Bautista 2001); for an absorber of a given column density \(N_H\) and ionization parameter \(\xi\), \textsc{XSTAR} is used to compute the absorption imprinted on a power-law X-ray spectrum. We compute a grid of \textsc{XSTAR} models, logarithmically sampling a range of column densities in the range \(N_H: 10^{20} – 10^{24} \ cm^{-2}\) and a range of ionization parameters in the range \(\xi: 1–10^4 \ erg \ cm^{-1} \ s^{-1}\), for use in spectral fitting. In the construction of the WA grids it is assumed that the irradiating power law has a spectral index of \(\Gamma = 2\), that elemental abundances are fixed to solar values,\(^{13}\) and that the turbulent velocity of the WA is 200 km s\(^{-1}\). Dramatic improvements in the goodness of fit are found by the inclusion in the model of three zones of WA. To begin with, each WA component is included assuming that the absorbing gas is at rest with respect to NGC 3783; the improvement in the fit upon the addition of each WA component was \(\Delta \chi^2 = -26316, -3096, \) and \(-2490\). The inclusion of a fourth zone led to a much smaller improvement in the fit and hence was deemed inappropriate. The residuals from the three-zone WA fit do indicate a soft excess. Following Krongold et al. (2003), we model the soft excess with a blackbody component (this is intended to be a phenomenological, not a physical, description of the soft excess; see discussion in Section 3.3) resulting in an improvement in the fit of \(\Delta \chi^2 / \Delta \nu = -480 / -2\) (i.e., \(\chi^2/\nu = 26582/13104\) (2.03)).

While providing a decent fit to the global spectrum, the model thus described leaves prominent unmodeled emission and absorption lines, the most prominent of which is the iron fluorescent emission line at 6.4 keV. Fitting the iron line with a simple Gaussian model improves the goodness of fit by \(\Delta \chi^2 / \Delta \nu = -593 / -3\), with a line energy \(E = 6.398 \pm 0.002\) keV (confirming the identification of cold iron K\(\alpha\)), FWHM = 2000 \pm 300 km s\(^{-1}\), and equivalent width \(W_{\text{K\(\alpha\)}} = 88 \pm 6\) eV. However, since we believe that this component originates from reflection, we shall henceforth model it using \textsc{pexmon}; replacing the simple Gaussian with the \textsc{pexmon} model convolved with a Gaussian velocity profile (with FWHM = 1800 \pm 300 km s\(^{-1}\)) results in a slightly better fit (\(\Delta \chi^2 = -18\)). At the soft end of the spectrum, the K\(\alpha\) emission triplet of O vii (at 0.574 keV, 0.569 keV, 0.561 keV) as well as the K\(\alpha\) emission line of O viii (at 0.654 keV) are clearly visible. Modeling these as Gaussian lines at the redshift of NGC 3783 with common velocity width yields a further improvement in the goodness of fit (\(\Delta \chi^2 = -218\)) with best-fitting FWHM = 700 \pm 150 km s\(^{-1}\) and equivalent widths \(W_{0.574} = 26 \pm 6\) eV, \(W_{0.569} = 14 \pm 6\) eV, \(W_{0.561} = 47 \pm 9\) eV, and \(W_{0.565} = 23 \pm 5\) eV.

It is well known that the WA in this and many other objects corresponds to outflowing gas. Relaxing the constraint that the WA zones are at the systemic redshift of NGC 3783 yields a large improvement in the fit (\(\Delta \chi^2 / \Delta \nu = 4247 / -3\); \(\chi^2/\nu = 21532/13094\) (1.64)), with implied line-of-sight outflow velocities in the 500–1000 km s\(^{-1}\) range. These velocities as well as the other parameters defining the best-fit model for the HETG data are listed in Table 1. The spectral model described in this section (power-law continuum, three-zone WA, blackbody soft excess, reflection from distant neutral material, and emission lines from O vii and O viii) describes the vast majority of spectral features seen in the HETG data (see Figure 3).

### 3.3. Global Modeling of the 0.7–45 keV Spectrum

To extract the maximal information from the full-band (0.7–45 keV) \textsc{Suzaku} spectrum of NGC 3783, we must compare the data to a global spectral model which is as physically self-consistent and realistic as possible. In constructing this global model, we draw guidance from our heuristic analysis of the hard-band spectrum (Section 3.1) as well as the results from the \textsc{Chandra}/HETG (Section 3.2). The primary continuum emission is taken to be a power law (photon index \(\Gamma\) ) with a soft excess which we describe as a blackbody (temperature \(T\)). X-ray reflection of this continuum from cold, distant material (possibly associated with the dusty/molecular torus of unified Seyfert schemes) is described using the \textsc{pexmon} model (see Section 3.1). As discussed in Section 3.1, the inclination of the \textsc{pexmon} is fixed at \(i = 60^\circ\) and the abundances are fixed to be solar, as defined in Nandra et al. (2007). These emission components are then absorbed by a three-zone WA modeled using the \textsc{XSTAR} tables described in Section 3.2; the column density \(N_H\) and ionization parameter \(\xi\) of each zone are taken to be free parameters rather than being fixed to the HETG value. Since the \textsc{Suzaku}/XIS detectors do not have the spectral resolution capable of constraining the outflow velocities of the various WA zones, we have elected to hold the redshifts of these components fixed at the cosmological value for NGC 3783. Statistically indistinguishable results are obtained if we, instead, fix the outflow velocities to the HETG-derived values. For completeness, we also allow for some fraction \(f_{\text{sc}}\) of the continuum to be scattered around (or to leak through) the WAs, i.e., our model allows for “partial covering.”

Fitting this model to the 0.7–45 keV \textsc{Suzaku} data results in a poor fit (\(\chi^2/\nu = 1206/679\) (1.78)) and strong residuals which indicate the presence of the broad iron line as well as additional reflection beyond that associated with the narrow iron line (Figure 4). This leads us to include relativistically smeared reflection from an ionized accretion disk into the spectral model; operationally, we use the ionized reflection model \textsc{relfionx} (Ross & Fabian 2005) convolved with the variable-spin relativistic smearing model \textsc{relconv} (Dauser et al. 2010). The \textsc{relconv} model is a further evolution of the \textsc{kerrconv} model of Brenneman & Reynolds (2006), employing faster and more accurate line-integration schemes and allowing black hole spin to be fit as a free parameter for prograde,

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\(^{13}\) http://heasarc.nasa.gov/lheasoft/xstar/docs/html/node41.html
While the fit achieved with this blurred reflection model is not statistically ideal (χ²/ν = 917/664 (1.38)), there are no broadband residuals (Figure 5(a)), and much of the contribution to the excess χ² originates from fine details of the WA-dominated region below 1.5 keV. The model is shown in Figure 5(b), and the best-fitting parameter values are shown in Table 1.

The parameters defining the best-fitting model for the 0.7–45 keV data are shown in Table 1 along with their 90% confidence ranges. Under the assumption that we can identify the low-, medium-, and high-ionization components seen in the 2001-HETG observation with those seen in our 2009-Suzaku data, we see that both the column density and the ionization state of the low-ionization absorber have increased somewhat (∆NWA ≈ 3 × 10³¹ cm⁻²). In contrast, the medium- and high-ionization absorbers have slightly dropped in ionization parameter. This is not surprising and is consistent with changes in the ionization state of these absorbers seen in the various WA zones.

We also note a change in the both the temperature and normalization of the blackbody component between the 2001-HETG and 2009-Suzaku data. This merits some discussion. The blackbody component used to phenomenologically parameterize the non-spinning, and retrograde spins (a ∈ [−0.998, 0.998]).

Table 1

| Model Component | Parameter | HETG | Suzaku (0.7–45 keV) | Suzaku (>3 keV) |
|-----------------|-----------|------|-------------------|-----------------|
| Galactic column | NH        | 9.91(1) | 9.91(1) | 9.91(1) |
| WAabs1          | NWA      | 127+17−2.0 | 159+31−31 | 159(1) |
|                 | log ξ    | 1.15+0.01−0.01 | 1.47+0.03−0.03 | 1.47(1) |
|                 | Δζ       | (1.4+0.05−0.07) × 10⁻³ | 0(f) | 0(f) |
| WAabs2          | NWA      | 268+42−1.12 | 168+48−48 | 168(1) |
|                 | log ξ    | 2.83+0.01−0.01 | 2.53+0.05−0.02 | 2.53(1) |
|                 | Δζ       | (3.4+0.4−0.4) × 10⁻⁴ | 0(f) | 0(f) |
| WAabs3          | NWA      | 90+10−0.14 | 91+9−9 | 91(1) |
|                 | log ξ    | 1.93+0.02−0.02 | 1.93(1) |
|                 | Δζ       | (1.0+0.3−0.3) × 10⁻³ | 0(f) | 0(f) |
| PL              | Γ        | 1.64+0.01−0.01 | 1.81+0.10−0.05 | 1.84+0.06−0.05 |
|                 | Apd      | (1.4+0.01−0.01) × 10⁻² | (1.46+0.09−0.04) × 10⁻² | (1.52+0.10−0.08) × 10⁻² |
| BB              | kT (eV)  | 107+33−0.4 | 60+3−4 | 60(1) |
|                 | Asb      | (1.4+0.1−0.1) × 10⁻⁴ | (8.45+5.96−5.7) × 10⁻³ | 8.45 × 10⁻³(f) |
| Scattered fraction | fscc | (2.3+0.4−1.0) × 10⁻² | 0.17+0.02−0.02 | 0.17(f) |
| Cold reflection | Rcold    | 0.49+0.04−0.03 | 0.46+0.12−0.07 | 0.62+0.13−0.20 |
| PL cutoff (keV) |          | ... | 200(f) | 200(f) |
| GAU line       | E (keV)  | ... | 6.97(f) | 6.97(f) |
|                 | σ (keV)  | ... | 0.0154(f) | 0.0154(f) |
|                 | Wpexmon (eV) | ... | 22+5−5 | 16+4−4 |
|                 | Apexmon (eV) | ... | (1.26+0.29−0.31) × 10⁻⁵ | (1.11+0.39−0.31) × 10⁻⁵ |
| Accretion disk | Zre      | 3.7+0.9−0.9 | 2.2+2.4−2.4 |
|                 | ξ        | ... | < 8 | < 67 |
|                 | Rdsl     | ... | 0.21+1.56−1.56 | 0.23×14.66−0.03 |
|                 | i        | ... | 22+3−8 | 19+6−14 |
|                 | rISCO    | ... | ISCO(f) | ISCO(f) |
|                 | q1       | ... | 5.2−0.7−0.8 | 4.7+1.9 |
|                 | q2       | ... | 5.4+1.9−0.9 | 6.0+3.9−3.9 |
|                 | q3       | ... | 2.9±0.2 | 2.8±0.5 |
|                 | rISCO    | ... | 400(f) | 400(f) |
| PIN/XIS norm    |          | ... | 1.18(f) | 1.15+0.07−0.07 |
| SMBH spin       | a        | ... | ≥0.98 | 0.98±0.02−0.34 |
| state of the low-ionization absorber have increased somewhat (∆NWA ≈ 3 × 10³¹ cm⁻²). In contrast, the medium- and high-ionization absorbers have slightly dropped in ionization parameter. Given that these different zones are likely at very different distances from the central engine with very different plasma densities, they will possess very different recombination/photoionization timescales and hence will respond to changes in the ionization flux on different timescales. Thus, it is not surprising that we see a mixture of increasing and decreasing ionization states in the various WA zones.

Notes. All errors are quoted at the 90% confidence level for one interesting parameter (Δχ² = 2.7). Parameters marked with an “(f)” had their values fixed during the fit. Units of normalization are in photons cm⁻² s⁻¹, column density is in units of 10⁶³ cm⁻², ionization parameter is in erg cm s⁻¹, iron abundance is relative to solar (linked between the reflexion and pexmon reflection components), inclination is in degrees, radii are in r₁, and spin parameter is dimensionless, but is defined as a ≡ c̈/GM². See Section 3 for details.
soft excess was first employed by Krongold et al. (2003), who found \( kT = 0.10 \pm 0.03 \) keV and \( A_{bb} = (2.0 \pm 0.7) \times 10^{-4} \), where the normalization is in units of \( \frac{L_{39}}{D_{10}} \) (\( L_{39} \) is luminosity of the component in units of \( 10^{39} \text{ erg s}^{-1} \) and \( D_{10} \) is distance to the source in units of \( 10 \text{ kpc} \)). Our analysis of the same HETG data confirms the Krongold et al. (2003) result. By contrast, our analysis of the Suzaku/XIS+PIN spectra finds a lower temperature \( (kT = 0.060^{+3}_{-1} \text{ keV}) \) and normalization that is almost two orders of magnitude greater \( (A_{bb} = 8.4^{+9}_{-7} \times 10^{-3}) \). We stress that neither the use of a blackbody to model the soft excess nor the precise change in the parameters of the blackbody should be interpreted literally. In particular, the significant change in the normalization of this component is misleading—the lower energy cutoffs in both the HETG analysis (0.5 keV) and the XIS analysis (0.7 keV) are much higher than the peak of this blackbody component and, thus, only the Wien tail of this component is playing any role in the spectral fitting. Given this fact, even a modest drop in the temperature must be compensated for by a large increase in normalization in order to have a comparable contribution to the observed energy band. While the physical nature of the soft excess is of intrinsic interest, it is beyond the scope of this paper. We have verified that different treatments of the soft excess (replacing the blackbody spectrum with bremsstrahlung or a steep power-law component) do not affect the interpretation of the spectrum above 2 keV.

The principal focus of this work is the signature of the relativistic accretion disk. Our global fit finds reflection from a rather low-ionization accretion disk \( (\xi < 9 \text{ erg cm}^{-1} \text{ s}^{-1}) \) extending down to the innermost stable circular orbit (ISCO) of a rapidly rotating black hole \( (a \gtrsim 0.98) \). The emissivity/irradiation profile defining the reflection spectrum, modeled as a broken power law, is found to have an inner power-law index of \( q_1 = 5.2^{+0.7}_{-0.5} \) breaking to \( q_2 = 2.9 \pm 0.2 \) at a radius of \( r_{br} = 5.4^{+1.9}_{-0.9} r_g \). If these indices are tied together in the model, i.e., if \( q_1 = q_2 \), the fit worsens considerably \( (\Delta \chi^2/\Delta v = +21/1) \), with \( q_1 = q_2 = 3.0 \pm 0.3 \) and the black hole spin is also less tightly constrained: \( a \gtrsim 0.25 \).

The iron abundance of the disk has been constrained to lie between 2.8 and 4.6 times solar. To probe the robustness of this constraint we have refitted the data in three different ways, each allowing for slight differences in the way the iron abundance was handled in our model: (1) fixing Fe/solar of the distant reflector (pexmon) to that of the inner disk reflection (reflionx), with both values frozen at Fe/solar = 1; (2) allowing these linked abundances allowed to vary freely; and (3) allowing both abundances to vary freely and independently. Compared with the global best fit, scenario (1) resulted in a worsening of the goodness of fit by \( \Delta \chi^2 = 33 \) and unconstrained black hole spin at the 90% confidence level, scenario (2) resulted in a marginal decrease in the goodness of fit by \( \Delta \chi^2 = 7 \).
Figure 4. Results of fitting the XIS+PIN spectrum with a model that includes the warm absorbers, distant reflection, and scattering/leaked soft component but not the relativistic ionized accretion disk. While the fitting is performed on the 0.7–45 keV spectrum, we show for clarity only the residuals above 3 keV. Left: strong residuals indicative of a broad iron line and Compton reflection hump are clearly visible. This motivates the inclusion of a relativistic disk component into the spectral model. The XIS 0+3 data are shown in black and XIS 1 data are in red, while the HXD/PIN data are in blue. The solid green line represents a data-to-model ratio of unity. Right: zoom-in on the Fe K line region.

Figure 5. Global modeling of the 0.7–45 keV XIS-FI+PIN data. The left panel shows the resulting residuals from fitting the model (including the relativistic accretion disk) discussed in Section 3.3. Data point colors are as in Figure 2. The right panel shows the best-fitting model color coded as follows: (a) green line, continuum power-law emission; (b) dark blue line, cold and ionized iron line emission from distant matter; (c) red line, soft excess modeled as blackbody; (d) magenta line, significant emission that scatters around or leaks through the warm absorber; (e) light blue line, relativistically smeared disk reflection; and (f) thick black line, total summed model spectrum. Warm absorption affects all components apart from (d). (no change in spin constraints), and scenario (3) yielded no change in the goodness of fit (no change in spin constraints).

In summary, the high iron abundance of the reflonx is statistically preferred to the solar value; the high-spin value is dependent upon the high iron abundance, but the high abundance is strongly preferred in the fit. Because the iron abundance of the distant reflector could not be constrained independently of the relativistic reflector, the pexmon and reflonx iron abundances have been linked in our best model fit.

To gauge the importance of the (complex) soft spectrum on our global fit, we have also conducted a restricted hard-band (3–45 keV) fit. Since a hard-band fit cannot constrain the parameters of the WA or soft excess, these parameters are constrained to lie within their 90% confidence ranges as derived from the 0.7–45 keV analysis. To be most conservative, we also relax the constraint on the XIS/PIN cross-normalization, allowing it to be a free parameter. The resulting fit is listed in the last column of Table 1. For this fit $\chi^2/\nu = 499/527 (0.95)$, a great improvement over the 0.7–45 keV fit and confirmation that the small residuals below $\sim 1.5$ keV are the primary contribution to the large reduced $\chi^2$ of the full spectral fit. While the parameter values are equivalent to those of the 0.7–45 keV fit within errors, the uncertainties on the parameters are larger when only the hard spectrum is considered. This is especially true for the inner disk emissivity and break radius of the relconv model, which exhibit a strong degeneracy without the soft spectrum data. Figure 6 shows the confidence contours on the $(q_1, q_2)$-plane for this hard-band fit; we see that the outer disk emissivity index, $q_2$, is well constrained, whereas the constraints on the inner disk emissivity index, $q_1$, are clearly worse. Fixing the XIS/PIN cross-normalization at the nominal value of 1.18 tightens the constraints but still leaves a significant degeneracy between $q_1$ and $r_{br}$ (Figure 6).

Using the best-fitting 0.7–45 keV spectral model with the XIS 0 normalization, the 2–10 keV observed-frame flux of NGC 3783 is $F_{2-10} = 6.04 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Adopting a standard cosmological model ($H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$), this implies a rest-frame luminosity...
of $L_{2-10} = 1.26 \times 10^{43}$ erg s$^{-1}$. The hard X-ray band yields a 16–45 keV flux of $F_{16-45} = 1.07 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ for a rest-frame luminosity of $L_{16-45} = 2.24 \times 10^{45}$ erg s$^{-1}$.

3.4. The Spin of the Black Hole

Our fiducial spectral model discussed above yields a spin constraint of $a \geq 0.98$ (90% confidence) or $a \geq 0.88$ (99% confidence). However, given the subtle nature of the spin measurements, it is useful to address the systematic issues that may be introduced by the modeling and analysis techniques.

We can assess the role of different analysis-related assumptions on the derived spin by comparing the variation of $\chi^2$ with $a$. Figure 7 (black line) shows $\Delta \chi^2(a) = \chi^2(a) - \chi^2_{\text{best-fit}}$ from our fiducial analysis that underlies the constraint just quoted. It is interesting to note the non-monotonic nature of the $\chi^2$-space above $a \sim 0.75$. We consider a few variants from this fiducial analysis in order to probe the sensitivity of the spin measurement. An important issue is the extent to which the WA parameters are trading off with the derived black hole spin. Thus, we repeat the analysis with the WA parameters (column densities and ionization parameters for all three zones) fixed at their best-fit values from the fiducial model. The resulting spin constraints are shown in Figure 7 ($\Delta \chi^2 = 3, 4.6, 9.2$), respectively. The dot-dashed black line represents $q_1 = q_2$. (A color version of this figure is available in the online journal.)

Second, to the extent that the strength of the Compton reflection hump is important, we may be concerned about the effect of cross-calibration errors in the flux normalization between the XIS and the PIN spectra. Thus, we repeat the spectral analysis, leaving the cross-normalization factor as a free parameter. The best-fit value is slightly smaller than our fiducial value (1.15 versus 1.18), but the improvement in the goodness of fit is only marginally significant ($\Delta \chi^2 = 6$ for one additional degree of freedom). The spin is constrained to be slightly smaller than that of the fiducial model (to 90% confidence, $a = 0.92$–0.95; Figure 7, blue line).

Lastly, we may be concerned that the spin fits are being driven by the contribution of the ionized disk to the high S/N by highly complex region of the spectrum below 1.5 keV. Thus, we have repeated our analysis including data only above 3 keV. Here, too, we allow the XIS/PIN cross-normalization to be a free parameter. Given the lack of data at soft energies to constrain them, the WA, blackbody, and scattered fraction components were frozen to their best-fitting values for the full-band, free cross-normalization case (which is, within errors, identical to the WA parameters for the fiducial model). Yet again, the best-fit spin parameter is similar to that of the fiducial model ($a \geq 0.95$; Figure 7, green line). This indicates that the fitted spin value is indeed driven by the Fe K band.

4. DISCUSSION AND CONCLUSIONS

The X-ray spectrum of NGC 3783 is complicated; in addition to the effects of a multi-zone WA, there are suggestions that some fraction (17%) of the primary X-ray emission can scatter around or leak through the WA. However, despite this complexity, the high S/N and broad bandpass of Suzaku allows us to robustly detect and study the relativistically smeared X-ray reflection spectrum from the surface of the inner accretion disk. Assuming
that the region within the general relativistic radius of 99% confidence does not contribute to the reflection spectrum (Reynolds & Fabian 2008) we determine a lower limit of η > 0.98 (90% confidence) to the dimensionless spin parameter of the black hole. Even at the 99% confidence level, we constrain the spin to be a > 0.88. Relaxing the assumed XIS/PIN cross-normalization or neglecting the soft-band data (but then freezing the WA parameters) allows the model to find a slightly better fit and makes the constraints slightly lower (a = 0.92–0.95, a > 0.95 at 99% confidence, respectively; a > 0.88, a > 0.90 at 99% confidence, respectively).

Including this result, four out of the eight AGNs with reliable spin measurements may have spins greater than a = 0.8 (see Table 2). Spin measurements for more sources are required before we can draw any conclusions about the spin distribution function, but here we note that there are potentially important selection effects biasing any flux-limited sample toward high-spin values. For standard accretion models, the efficiency of black hole accretion increases as the spin of the black hole increases. So, all else being equal, an accreting, rapidly spinning black hole will be more luminous than an accreting, slowing spinning black hole and hence will be overrepresented in flux-limited samples.

We illustrate this effect by calculating the selection bias given some very simple assumptions. Suppose that a flux-limited sample is constructed in some band B. The accretion luminosity in that band will be given by

\[ L = K_B \eta \dot{M} c^2 \]  

where \( K_B \) is the fraction of luminosity appearing in band \( B \) (i.e., the reciprocal of the bolometric correction), \( \eta \) is the accretion efficiency, and \( \dot{M} \) is the mass accretion rate. Now let us assume that \( \dot{M} \) has no explicit spin dependence (e.g., is determined by the larger circumbulge environment), and that the spectral energy distribution and hence \( K_B \) is independent of spin. Thus, the space density of sources with accretion rates in the range \( \dot{M} \rightarrow \dot{M} + d\dot{M} \) and spins in the range \( a \rightarrow a + da \), denoted \( \Phi(\dot{M}, a) \) \( d\dot{M} \) \( da \), can be taken as a given function set by the astrophysics of black hole growth.

We assume a Euclidean universe, valid for the local/bright AGN samples relevant for spin measurements with the current generation of X-ray observatories. The number of sources in a flux-limited sample with luminosity in the range \( L \rightarrow L + dL \) and spins in the range \( a \rightarrow a + da \) is then

\[ dN \propto \Phi(L, a) L^{3/2} dL \, da, \]  

(2)

where \( \Phi(L, a) \) \( dL \) \( da \) is the space density of sources with luminosity in the range \( L \rightarrow L + dL \) and spins in the range \( a \rightarrow a + da \). Transforming into the \((\dot{M}, a)\)-plane gives

\[ dN \propto \Phi(\dot{M}, a) \eta^{3/2} \dot{M} d\dot{M} \]  

(3)

Using our assumption that the mass accretion rate is independent of spin, we can separate \( \Phi(\dot{M}, a) \) into an accretion-rate-dependent space density \( n(\dot{M}) \) and a spin distribution function \( f(a) \), \( \Phi(\dot{M}, a) = n(\dot{M}) f(a) \). We can then integrate Equation (3) over \( \dot{M} \) in order to determine the number of sources in a flux-limited sample with spins in the range \( a \rightarrow a + da \):
$a_{\text{max}} = 0.95$, then half of the sources in the flux-limited sample will have $a > 0.67$; for $a_{\text{max}} = 0.99$ we find that half of the sources in the sample have $a > 0.73$.

Generalizing away from a flat spin distribution, we can consider spin distribution functions of the form $f(a) \propto a^p$. Within this simple framework, we require $f(a) \propto a$ (i.e., $p = 1.0$) in order to produce flux-limited samples where half of the sources have $a > 0.84$ (assuming $a_{\text{max}} = 0.95$). For high-spin-weighted distribution functions such as this, the selection bias is stronger; only 20% of objects in the volume-limited parent sample actually have $a > 0.84$. Of course, given the small number statistics and highly inhomogeneous selection functions for the current spin measurements, it is too early to draw any conclusions about the need for a high-spin-biased distribution function.

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