Acta Polytechnica **53**(Supplement):652–658, 2013
`doi:10.14311/AP.2013.53.0652`

MEASURING SUPERMASSIVE BLACK HOLE SPINS IN AGN

Laura Brenneman*

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS-67, Cambridge, MA 02138 USA
* corresponding author: `lbrenneman@cfa.harvard.edu`

Abstract. Measuring the spins of supermassive black holes (SMBHs) in active galactic nuclei (AGN) can inform us about the relative role of gas accretion vs. mergers in recent epochs of the life of the host galaxy and its AGN. Recent theoretical and observation advances have enabled spin measurements for ten SMBHs thus far, but this science is still very much in its infancy. Herein, I discuss how we measure black hole spin in AGN, using recent results from a long Suzaku campaign on NGC 3783 to illustrate this process and its caveats. I then present our current knowledge of the distribution of SMBH spins in the local universe. I also address prospects for improving the accuracy, precision and quantity of these spin constraints in the next decade and beyond with instruments such as *NuSTAR*, *Astro-H* and future large-area X-ray telescopes.

Keywords: black holes, active galaxies, X-rays, spectroscopy, *XMM-Newton*, *Suzaku*, *NuSTAR*, NGC 3783.

1. Introduction

Measurements of the spins of supermassive black holes (SMBHs) in active galactic nuclei (AGN) can contribute to the understanding of these complex and energetic environments in three principal ways:

- They offer a rare probe of the nature of the spacetime proximal to the event horizon of the black hole (BH), well within the strong-field gravity regime [12, 19];
- They can shed light on the relation of a black hole's angular momentum to its outflow power in the form of winds and jets (e.g., [26, 33, 37];
- They can inform us about the relative role of gas accretion vs. mergers in recent epochs of the life of the host galaxy and its AGN [3].

For these reasons, developing a theoretical and observation framework in which to measure black hole spin accurately and precisely is of critical importance to our understanding of how galaxies form and evolve over cosmic time.

Advances in theoretical modeling as well as observational sensitivity in the *Chandra/XMM-Newton/Suzaku* era are finally producing robust constraints on the spins of a handful of SMBHs. Computationally, new algorithms developed within the past decade [2, 6, 9, 11] have made it possible to perform fully relativistic ray-tracing of photon paths emanating from the accretion disk close to the BH, keeping the BH spin as a variable parameter in the model. When such models are fit to high signal-to-noise (S/N) X-ray spectra from the innermost accretion disk, they yield vital physical information about the BH/disk system, including constraints on how fast – and in what direction – the BH is rotating. If spin (formally denoted $a \equiv cJ/GM^2$, where c is the speed of light, J is the BH angular momentum, G is Newton's constant and M is the mass of the BH) is known to within $\Delta a \leq 10\%$, then meaningful correlations between spin and other environmental variables (e.g., jet power, history of the accretion flow) can be drawn.

In this proceeding, I discuss our current knowledge of the distribution of SMBH spins in the local universe and future directions of BH spin research. I begin in §2 with an examination of the spectral modeling techniques used to measure BH spin in AGN. I then discuss the application of these techniques to a deep observation of NGC 3783, and the caveats that must be considered in §3. I describe the results of these and other investigations of BH spin in bright, nearby type 1 AGN in §4, examining our current knowledge of the spin distribution of local SMBHs and its implications. Conclusions and future directions for this field of research are presented in §5.

2. Measuring black hole spin

In principle, there are at least five ways that the spin of a single (i.e., non-merging) BH can be measured, electromagnetically. All five are predicated on the assumption that General Relativity provides the correct description of the spacetime near the BH, and that there is an easily-characterized, monotonic relationship between the radius of the innermost stable circular orbit (ISCO) of the accretion disk and the BH spin (see Fig. 1). These five methods are listed below.

- **Thermal Continuum Fitting** (e.g., McClintock et al. [21]).
- **Inner Disk Reflection Modeling** (e.g., Brenneman & Reynolds [6]).

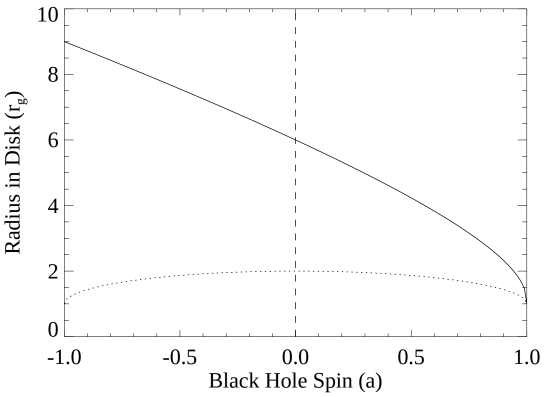

FIGURE 1. Radius of the ISCO (solid line) and event horizon (dotted line) as a function of BH spin. Spin values to the left of the dashed line indicate a BH spinning in he retrograde direction relative to the accretion disk, while spins to the right of the dashed line indicate prograde BH spin relative to the disk.

- **High Frequency Quasi-Periodic Oscillations** (e.g., Strohmayer [34]).
- **X-ray Polarimetry** (e.g., Tomsick et al. [38]).
- **Imaging the Event Horizon Shadow** (e.g., Broderick et al. [7]).

There are currently limitations in applying the last three methods listed above, and the continuum fitting method is only viable for stellar-mass BHs, due principally to the difficulty in finding AGN in a thermally dominant state analagous to the high/soft state seen in black hole X-ray binaries (e.g., Czerny et al. 2011). We are therefore restricted to using only the reflection modeling method for constraining the spins of SMBHs in AGN at this time. This method assumes that the high-energy X-ray emission (≥ 2 keV) is dominated by thermal disk emission which has been Comptonized by hot electrons in the "corona," whether this structure represents the disk atmosphere, the base of a jet or some alternative geometry. Some of the scattered photons will depart the system and form the power-law continuum characteristic of typical AGN in X-rays. A certain percentage of the photons, however, will be scattered back down ("reflected") onto the surface of the disk again, exciting a series of fluorescent emission lines of various species ≤ 7 keV, along with a "Compton hump" shaped by the Fe K absorption edge at ~ 7.1 keV and by downscattering at $\sim 20 \div 30$ keV. The most prominent of the fluorescent lines produced is Fe Kα at a rest-frame energy of 6.4 keV, due largely to its high fluorescent yield. As such, the Fe Kα line is the most important diagnostic feature of the inner disk reflection spectrum; its shape is altered from the typical near-delta function expected in a laboratory, becoming highly broadened and skewed due to the combination of Doppler and relativistic effects close to the BH (see Fig. 2). The energy at which the "red" wing of this line manifests is directly linked to the location of the ISCO, and therefore the spin of the BH (see [23, 31] for comprehensive reviews of the reflection modeling technique).

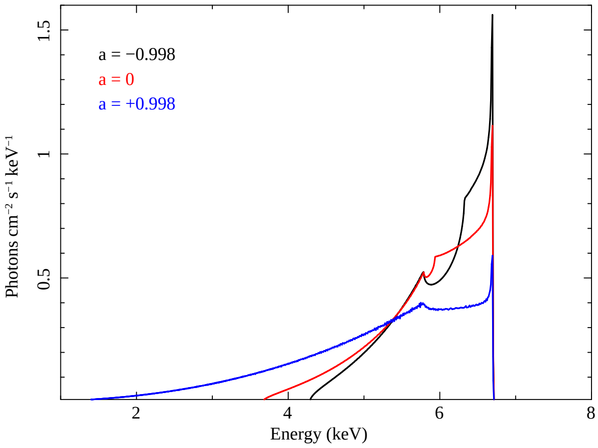

FIGURE 2. Change in the shape of the Fe Kα line as a function of BH spin. The black line represents $a = +0.998$, the red line shows $a = 0.0$ and the blue line shows $a = -0.998$.

3. APPLYING THE REFLECTION MODELING METHOD

An AGN must satisfy three important requirements in order to be a viable candidate for obtaining spin constraints. Firstly, it must be bright enough in order to be observed with the necessary S/N in X-rays to accurately separate the reflection spectrum from the continuum and any intrinsic absorption within the host galaxy. Typically one must obtain $\geq 200\,000$ counts from $2 \div 10$ keV [17], though in practice the required number can be substantially higher in sources with complex absorption. Secondly, the AGN must possess a broad Fe Kα line of sufficient strength relative to the continuum to allow its red wing to be successfully located; usually this corresponds to a line equivalent width of hundreds of eV (e.g., MCG–6-30-15, [6, 8, 24]). Not all type 1 AGN have been observed to possess such features. Recent surveys of hundreds of AGN with *XMM-Newton* have concluded that broadened Fe Kα lines are only present in $\sim 40\,\%$ of all bright, nearby type 1 AGN [10, 25]), and some broad iron lines have been ephemeral, appearing and disappearing in the same object observed during different epochs (e.g., NGC 5548, [5]). Thirdly, the Fe Kα line in question must be *relativistically* broad in order to be able to constrain BH spin; that is, it must have a measured inner disk edge – assumed to correspond to the ISCO – of $r_{\rm in} \leq 9\,r_{\rm g}$, where $r_{\rm g} \equiv GM/c^2$. Taking all these points into consideration, the potential sample size of spin measurements for AGN in the local universe is $\sim$ 30–40 sources [23]. Most of these AGN are type 1, lacking significant obscuration by dust and gas along the line of sight to the inner disk.

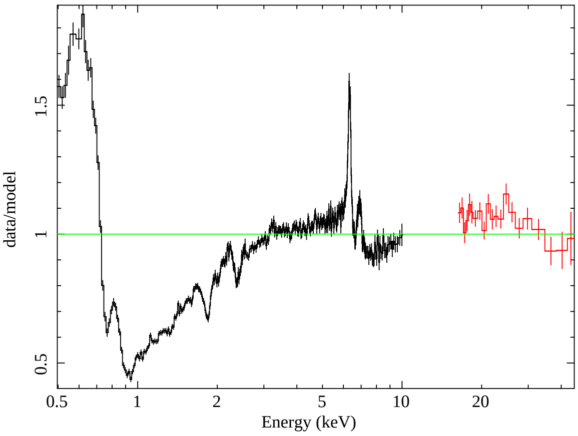

Figure 3. *Suzaku* XIS-FI (front-illuminated; black crosses) and PIN (red crosses) data from the 210 ks observation of NGC 3783 in 2009, ratioed against a simple power-law model for the continuum affected by Galactic photoabsorption. Black and Red solid lines connect the data points and do not represent a model. The green line represents a data-to-model ratio of unity. Data from the XIS back-illuminated CCD (XIS-BI) are not shown for clarity.

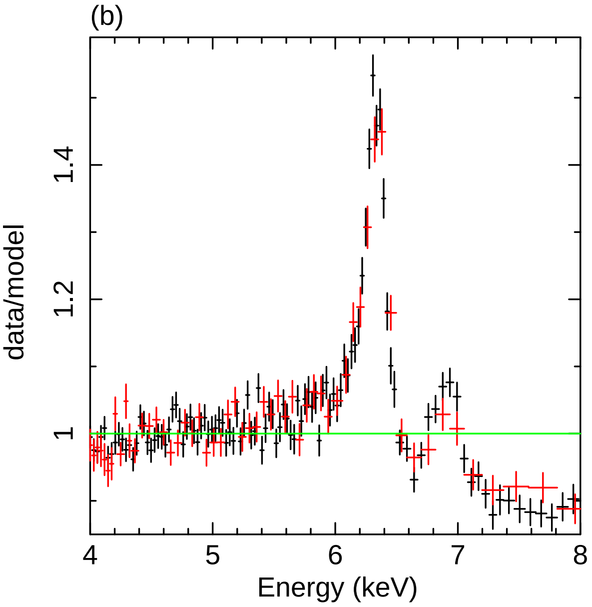

Figure 4. A zoomed-in view of the Fe K region in the 2009 *Suzaku* observation of NGC 3783, ratioed against a simple power-law continuum. Note the prominent narrow Fe Kα emission line at 6.4 keV and the blend of Fe Kβ and Fe XXVI at ∼ 7 keV. XIS-FI is in black, XIS-BI in red.

The reflection spectrum from the inner disk can be self-consistently reproduced by models such as `reflionx` [32] or `xillver` [14]. These models simulate not only the broad Fe Kα line, but all other fluorescent emission species at lower energies, as well as the Compton hump at higher energies. In order to incorporate the effects of relativity and Doppler shift, this static reflection spectrum must then be convolved with a smearing kernel which computes the photon trajectories and energies during transfer from the accretion disk to the observer. Several free-spin smearing algorithms are currently available for use (see §1). The `kerrconv` algorithm of Brenneman and Reynolds [6] is the only one of these models that is currently built into XSPEC, though it limits BH spin to prograde scenarios only. A more recent improvement is the `relconv` model of Dauser et al. [9], which generalizes the possible spins to incorporate retrograde BHs.

In the following Section, I describe the practicalities of using the `reflionx` and `relconv` models to measure the spin of the SMBH in NGC 3783 using a 210 ks *Suzaku* observation.

3.1. Case study: NGC 3783

The type 1 AGN NGC 3783 ($z = 0.00973$) was the subject of a deep *Suzaku* observation from 2009 as part of the *Suzaku* AGN Spin Survey Key Project (PI: C. Reynolds, lead co-I: L. Brenneman). The source was observed with an average flux of $F_X = 6.04 \times 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ from $2 \div 10$ keV during the observation, yielding a total of ∼ 940 000 photon counts over this energy range in the XIS instruments (S/N = 35) and ∼ 45 000 photon counts for the PIN instrument from $16 \div 45$ keV (S/N = 5), after background subtraction [4].

The spectrum is shown in Fig. 3 as a ratio to the power-law continuum and Galactic photoabsorbing column in order to illustrate the various residual spectral features present. The Compton hump is readily apparent ≥ 10 keV, though its curvature is relatively subtle compared with more prominent features of its kind (e.g., in MCG–6-30-15). The $6 \div 7$ keV band of the spectrum is dominated by narrow and broad Fe K features, including a narrow Fe Kα emission line at 6.4 keV and a blend of Fe Kβ and Fe XXVI emission at ∼ 7 keV. The broad Fe Kα line manifests as an elongated, asymmetrical tail extending redwards of the narrow Fe Kα line to ∼ $4 \div 5$ keV. The Fe K region can be seen in more detail in Figs. 4 and 5. At energies below ∼ 3 keV the spectrum becomes concave due to the presence of complex, ionized absorbing gas within the nucleus of the galaxy; the gas is ionized enough that some contribution from this absorber is seen at ∼ 6.7 keV in an Fe XXV absorption line. There is a rollover back to a convex shape below ∼ 1 keV, however, where the soft excess emission dominates.

The models described above were used by Brenneman [4] to fit the $0.7 \div 45$ keV *Suzaku* spectrum of NGC 3783 with a statistical quality of $\chi^2/\nu = 917/664\,(1.38)$. Most of the residuals in the best-fit model manifested below ∼ 3 keV in the region dominated by the warm absorber and soft excess, as is typical for type 1 AGN. Because the S/N of the XIS detectors is highest at lower energies due to the higher collecting area there, small residuals

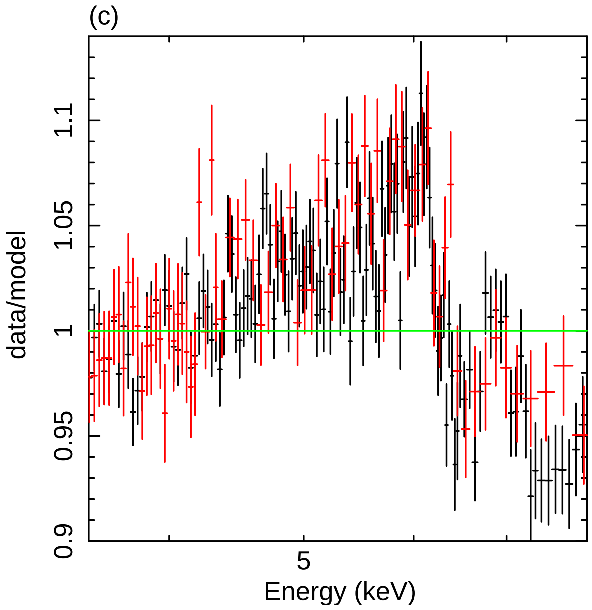

Figure 5. The broad Fe Kα line at 6.4 keV becomes more obvious when the two more prominent narrow emission lines are modeled out, in addition to the power-law continuum.

in the spectral modeling of this region can have an exaggerated effect on the overall goodness-of-fit. Excluding energies below 3 keV in our fit, we achieved $\chi^2/\nu = 499/527\,(0.95)$. No significant residuals remained.

The best-fit parameters of the BH/inner disk system included a spin of $a \geq +0.98$, a disk inclination angle of $i = 22^{+3}_{-8}$ deg to the line of sight, a disk iron abundance of Fe/solar $= 3.7 \pm 0.9$ and an ionization of $\xi \leq 8\,\mathrm{erg\,cm\,s^{-1}}$ (errors are quoted at 90 % confidence for one interesting parameter). These parameters remained consistent, within errors, when energies ≤ 3 keV were ignored in the fit, negating the importance of the soft excess emission in driving the fit to these parameter values.

By contrast, Patrick et al. [27] analyzed the same data separately and reached a strikingly different conclusion regarding the spin of the BH in NGC 3783, with approximately equivalent goodness-of-fit to that obtained by Brenneman [4]: $a \leq -0.04$. This discrepancy illustrates the importance of assumptions and modeling choices in influencing the derived BH spin and other physical properties of the BH/disk system. Patrick et al. [27] made three critical assumptions that differed from [4]:

(1.) that the iron abundance of the inner disk is fixed to the solar value;

(2.) that the warm absorber has a high-turbulence ($v_{\mathrm{turb}} = 1000\,\mathrm{km/s}$), high-ionization ($\xi \sim 7400\,\mathrm{erg\,cm\,s^{-1}}$) component not reported by Brenneman [4];

(3.) that the soft excess originates entirely through Comptonization, with the Comptonizing medium having a temperature of $kT \geq 9.5$ keV and an optical depth of $\tau = 1.9 \pm 0.1$.

Using a Markov Chain Monte Carlo approach, Reynolds et al. [29] demonstrated that a solar iron abundance is significantly detrimental to the global goodness-of-fit ($\Delta\chi^2 = +36$) in NGC 3783 when compared with allowing the iron abundance of the inner disk to fit freely. Brenneman [4] found no need to include a high-turbulence component in their fit to the *Suzaku* data, and noted no evidence for such a component in the higher-resolution 2001 *Chandra*/HETG data. Finally, Reynolds et al. [29] note that there is no physical reason to assume that the soft excess originates entirely from Comptonization, as other processes within the AGN might contribute (e.g., photoionized emission, scattering, thermal emission). Reynolds et al. [29] attempted several different model fits to the soft excess and found not only a much smaller contribution to the overall model for the soft excess component than Patrick et al. [27], but also no statistical difference between fits using different models (e.g., blackbody vs. `compTT`). It should be noted, however, that modeling the soft excess with a Comptonization component of high temperature, high optical depth and high flux, as Patrick et al. [27] have done, requires the `compTT` component to possess significant curvature up into the Fe K band, reducing the need for the relativistic reflection to account for this same curvature seen in the data and thereby eliminating the requirement of high BH spin. Clearly, different modeling approaches can lead to vastly different conclusions regarding BH spin and careful consideration should be given to the models used and their allowed parameter ranges. Obtaining high S/N X-ray spectra over a broad energy range (e.g., by using *NuSTAR* simultaneously with *XMM-Newton* or *Suzaku*) will also help break the degeneracy between models (see §5).

4. Results and implications

In the previous two sections we have noted the importance of both adequate data (i.e., high S/N) and a physically self-consistent modeling approach to constraining SMBH spins in AGN. We have also stressed the importance of one very critical assumption that must be made in order to calculate BH spin: namely, that the inner edge of the accretion disk is at the ISCO. If the optically-thick disk is truncated further out, then any spin derived using this assumption and the reflection modeling technique will be a lower limit. If there is some emission produced inside the ISCO, this will lead to a systematic error on the BH spin measurement that can be ≥ 20 % above the actual value of spin for non-spinning or retrograde BHs, but is ≤ 2 % higher than the real spin for BHs with spins $a \geq +0.9$ [30].

The models currently used to represent both the accretion disk and the relativistic smearing also have

AGN	a	$W_K\alpha$	log M	$L_{\rm bol}/L_{\rm Edd}$	Host
MCG–6–30–15	≥ 0.98	305^{+20}_{-20}	$6.65^{+0.17}_{-0.17}$	$0.40^{+0.13}_{-0.13}$	E/S0
Fairall 9	$0.52^{+0.19}_{-0.15}$	130^{+10}_{-10}	$8.41^{+0.11}_{-0.11}$	$0.05^{+0.01}_{-0.01}$	Sc
SWIFT J2127.4+5654	$0.6^{+0.2}_{-0.2}$	220^{+50}_{-50}	$7.18^{+0.07}_{-0.07}$	$0.18^{+0.03}_{-0.03}$	—
1H0707–495	≥ 0.98	1775^{+511}_{-594}	$6.70^{+0.40}_{-0.40}$	$\sim 1.0_{-0.6}$	—
Mrk 79	$0.7^{+0.1}_{-0.1}$	377^{+47}_{-34}	$7.72^{+0.14}_{-0.14}$	$0.05^{+0.01}_{-0.01}$	SBb
Mrk 335	$0.70^{+0.12}_{-0.01}$	146^{+39}_{-39}	$7.15^{+0.13}_{-0.13}$	$0.25^{+0.07}_{-0.07}$	S0a
NGC 7469	$0.69^{+0.09}_{-0.09}$	91^{+9}_{-8}	$7.09^{+0.06}_{-0.06}$	$1.12^{+0.13}_{-0.13}$	SAB(rs)a
NGC 3783	≥ 0.98	263^{+23}_{-23}	$7.47^{+0.08}_{-0.08}$	$0.06^{+0.01}_{-0.01}$	SB(r)ab
Ark 120	$0.94^{+0.1}_{-0.1}$	105^{+26}_{-24}	$8.18^{+0.05}_{-0.05}$	$0.04^{+0.01}_{-0.01}$	Sb/pec
3C 120	≤ -0.1	48^{+10}_{-10}	$7.74^{+0.20}_{-0.22}$	$0.31^{+0.20}_{-0.19}$	S0

Table 1. Summary of black hole spin measurements derived from in SMBH spectra. Data are taken with *Suzaku* except for 1H0707−495, which was observed with *XMM-Newton*, and MCG–6-30-15, in which the data from *XMM* and *Suzaku* are consistent with each other. For references, see [4]. Spin (a) is dimensionless, as defined previously. $W_{K\alpha}$ denotes the equivalent width of the broad iron line relative to the continuum in units of eV. M is the mass of the black hole in solar masses, and $L_{\rm bol}/L_{\rm Edd}$ is the Eddington ratio of its luminous output. Host denotes the galaxy host type. Host types for 1H0707−495 and SWIFT J2127.4+5654 are unknown. The spin values of MCG–6-30-15 and NGC 3783 are disputed by Patrick et al. [27].

their inherent limitations and uncertainties. The `reflionx` and `xillver` models both assume that the disk has a constant density and ionization structure throughout, which cannot be the case, physically. There is also some question about whether a limb-brightening vs. limb-darkening algorithm should be used to represent the directionality of the reflected emission from the disk when convolved with the smearing kernel [35]. The nature of the disk emissivity profile itself is also an active topic of research; though the disk is thought to dissipate energy as a function of radius ($\epsilon \propto r^{-q}$), the emissivity index (q) likely varies as a function of radius as well [40].

Taking all these caveats into account, one can begin to appreciate why, to date, there are only ten different AGN with published values for their SMBH spins. These AGN, and their properties, are listed in Tab. 1.

It is difficult to draw any robust statistical inferences from a sample size of ten objects. There may also be selection biases in play which make it more likely that we measure higher spin values [4]. The only pattern that is readily apparent in Tab. 1 is that nine out of ten AGN have relatively high, prograde SMBH spins. The one retrograde spin value is for 3C 120, which is the one AGN in the sample that is radio-loud. This may not be a coincidence; Garofalo [16] postulated that jet power is maximized for rapidly-rotating retrograde BHs (though this idea is not without controversy, e.g., [37]). More work needs to be done to assess BH spin and jet power independently in order to prove or disprove this conjecture.

If the trend toward large prograde spins continues to hold as our sample size increases, we might ultimately infer that the growth of bright, nearby AGN in recent epochs has been driven primarily by prolonged, prograde accretion of gas. If the overall distribution of SMBH spins in the local universe begins to drift toward intermediate values, it is likely that the role of mergers has been more significant than that of ordered gas accretion. Similarly, if the distribution tends toward low values of spin, we can infer that episodes of randomly-oriented accretion have been the dominant means of SMBH and galaxy growth [3].

5. Conclusions and future directions

Measuring BH spin is painstaking work, even with the best data from current observatories such as *XMM-Newton* and *Suzaku*. Long observations (c. hundreds of kiloseconds) of bright AGN are needed, and multi-epoch, multi-instrument data should be analyzed jointly whenever possible in order to assess the physical nature and variability of all of the components in a given X-ray spectrum. A broad energy range is also desirable in order to constrain the properties of the continuum and complex absorption, particularly, and to distinguish these components from any signatures of inner disk reflection. Only by isolating the broad Fe Kα line and its associated Compton hump can we measure BH spin with the accuracy and precision necessary to begin constructing a spin distribution for local AGN. We can then begin to draw inferences regarding the dominant growth mechanism of these SMBHs over cosmic time, and to understand the role of spin in jet production and AGN feedback.

Our current sample of ten AGN with measured, published SMBH spins must be extended in order to accomplish these goals. The *Suzaku* Spin Survey is ongoing, and is expected to provide new spin constraints for 3C 120 and Mrk 841 within the next year. Additionally, many valuable datasets from the *XMM* and *Suzaku* archives are currently being analyzed with an eye toward measuring spin (e.g., Walton et al., in prep.). *NuSTAR* [18] will also benefit this science, providing an invaluable high-energy ($\sim 5 \div 80\,\mathrm{keV}$) complement to *XMM-Newton* and *Suzaku* when used simultaneously with either observatory. Accessing this high energy range with low background and high S/N will enable the continuum and absorption in the spectrum to be more accurately modeled, allowing the signatures of inner disk reflection to be isolated and yielding more accurate, precise spin constraints.

In addition to *NuSTAR*'s role in this work, *Astro-H* [36], scheduled for launch in 2014, will bring the science of micro-calorimetry to X-ray astronomy with a spectral resolution of $\Delta E \sim 7\,\mathrm{eV}$ over the $0.3 \div 12\,\mathrm{keV}$ range. The calorimeter will be the unique strength of this mission, enabling the broad and narrow Fe K emission and absorption features to be definitively disentangled and the telltale signatures of complex intrinsic absorption to be identified and modeled correctly.

In order to achieve the order-of-magnitude increase in sample size necessary to begin assessing the spin distribution of SMBHs in the local universe from a statistical perspective, future large-area ($\geq 1\,\mathrm{m}^2$) X-ray observatories are needed. Proposed concepts such as *IXO* [39], *ATHENA* [1] and the *Extreme Physics Explorer* (EPE) [15] would all offer the necessary collecting area and spectral resolution to extend our sample of measured SMBH spins to several hundred AGN using the reflection modeling method. *LOFT* [13] would also bring precise timing resolution into play along with large collecting area, allowing measurements of spin to be made on the orbital timescale of many AGN by tracing individual hot spots in the inner accretion disk.

The science of determining BH spin is very much in its infancy. Though the past decade has seen great strides in our ability to constrain spin through long X-ray observations coupled with detailed spectral modeling, much work remains to be done in terms of improving the precision and accuracy of these measurements, as well as the sample size. The next decade will see an improvement in the quality of BH spin science, but a significant advance in the quantity of this work in the decades beyond will depend critically on the amount of international funding available for large-area X-ray missions.

Acknowledgements

LB is indebted to the Vulcano conference organizers for their kind invitation, and to NASA grant # NNX10AR44G, which funded her travel.

References

[1] Barcons, X. et al.: 2012, arXiv:1207.2745

[2] Beckwith, K. & Done, C.: 2005, *Mon. Not. R. astr. Soc.*, 359, 1217

[3] Berti, E. & Volonteri, M.: 2008, *Astrophys. J.*, 684, 822

[4] Brenneman, L. et al.: 2011, *Astrophys. J.*, 736, 103

[5] Brenneman, L. et al.: 2012, *Astrophys. J.*, 744, 13

[6] Brenneman, L. & Reynolds, C.: 2006, *Astrophys. J.*, 652, 1028

[7] Broderick, A. et al.: 2011, *Astrophys. J.*, 735, 57

[8] Chiang, C.Y. & Fabian, A.: 2011, *Mon. Not. R. astr. Soc.*, 414, 2345

[9] Dauser, T. et al.: 2010, *Mon. Not. R. astr. Soc.*, 409, 1534

[10] de le Calle Pérez et al.: 2010, *Astr. Astrophys.*, 524, 50

[11] Dovčiak, M., Karas, V. & Yaqoob, T.: 2004, *Astrophys. J. Suppl.*, 153, 205

[12] Fabian, A. et al.: 1989, *Mon. Not. R. astr. Soc.*, 238, 729

[13] Feroci, M. et al.: 2010, *Soc. Pho. Inst. Eng.*, 7732E, 57

[14] Garcia, J. & Kallman, T.: 2010, *Astrophys. J.*, 718, 695

[15] Garcia, M. et al.: 2011, *Soc. Pho. Inst. Eng.*, 8147E, 55

[16] Garofalo, D.; 2009, *Astrophys. J.*, 699, 400

[17] Guainazzi, M. et al.: 2006, *Astron. Nachr.*, 327, 1032

[18] Harrison, F. et al.: 2005, *Exp. Astr.*, 20, 131

[19] Laor, A.: 1991, *Astrophys. J.*, 376, 90

[20] Malizia, A. et al.: 2008, *Mon. Not. R. astr. Soc.*, 389, 1360

[21] McClintock, J. et al.: 2006, *Astrophys. J.*, 652, 518

[22] McHardy, I. et al.: 2005, *Mon. Not. R. astr. Soc.*, 359, 1469

[23] Miller, J.: 2007, *Ann. Rev. Astr. Astrophys.*, 45, 441

[24] Miniutti, G. et al.: 2007, *Publ. astr. Soc. Japan*, 59S, 315

[25] Nandra, K. et al.: 2007, *Mon. Not. R. astr. Soc.*, 382, 194

[26] Narayan, R. & McClintock, J.: 2012, *Mon. Not. R. astr. Soc.*, 419L, 69

[27] Patrick, A. et al.: 2011b, *Mon. Not. R. astr. Soc.*, 416, 2725

[28] Peterson, B. et al.: 2004, *Astrophys. J.*, 613, 682

[29] Reynolds, C. et al.: 2012, arXiv:1204.5747

[30] Reynolds, C. & Fabian, A.: 2008, *Astrophys. J.*, 679, 1181

[31] Reynolds, C. & Nowak, M.: 2003, *Phys. Reports*, 377, 389

[32] Ross, R. & Fabian, A.: 2005, *Mon. Not. R. astr. Soc.*, 358, 211

[33] Steiner, J. et al. : 2012, *Astrophys. J.*, 745, 136

[34] Strohmayer, T.: 2001, *Astrophys. J.*, 552L, 49

[35] Svoboda, J. et al. : 2010, *Amer. Inst. Phys. Conf.*, 1248, 515

[36] Takahashi, T. et al. , 2010, *Soc. Pho. Inst. Eng.*, 7732E, 27

[37] Tchekhovskoy, A. & McKinney, J.; 2012, *Mon. Not. R. astr. Soc.*, 423L, 55

[38] Tomsick, J. et al. : 2009, arXiv:0902.4238

[39] White, N. et al. : 2010, *Amer. Inst. Phys. Conf.*, 1248, 561

[40] Wilkins, D. & Fabian, A.: 2010, *Mon. Not. R. astr. Soc.*, 414, 1269

[41] Woo, J.H. & Urry, C.M.: 2002, *Astrophys. J.*, 579, 530

[42] Zoghbi, A. et al. : 2010, *Mon. Not. R. astr. Soc.*, 401