Measuring the Spins of Stellar-Mass Black Holes

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1. Introduction and Scientific Context

"If the cosmological problem is the number one problem of astronomy, then problem number two should be the problem of black holes[1]." These words of Nobelist V. L. Ginzburg from the 1980s ring true today. Furthermore, the two problems are inextricably linked because the nascent Universe can only be compared to a black hole (BH). In addition, the evolution of the Universe is profoundly affected by the presence of BHs. For example, BHs power AGN, which interact with and greatly modify their host galaxies and clusters; and they are an ultimate endpoint of stellar evolution, with one percent or so of the Milky Way's baryons having already been swept away into stellar-mass BHs.

With no useful theory of quantum gravity on the horizon, fundamental physics is stymied. In this instance, astronomy can serve physics by prosecuting the study of astronomical BHs, possibly the only kind of BH that we will ever know. In doing so, it is wise to take our cue from the study of cosmology where no stone is left unturned, where the study of the CMB, supernovae, galaxy clusters, GRBs, quasars, galactic and stellar evolution, etc., all play important roles in digging deep. For BHs likewise, it makes sense to pursue with equal vigor both supermassive and stellar-mass BHs, while seeking dynamical evidence for intermediate-mass BHs.

And it is equally important to use all available data channels. We can reasonably expect that LIGO and LISA will provide us with intimate knowledge concerning BHs. However, gravitational wave detectors are unlikely to tell us much about MHD accretion flows in strong fields or the origin of relativistic jets or about relativistically-broadened Fe lines and high-frequency quasi-periodic oscillations, phenomena that are now routinely observed for BHs[2]. In short, observations of *accreting* BHs show us uniquely how a BH interacts with its environment. It behooves us to explore widely because, as in cosmology, it is the synergistic exploration of all paths that enlightens. Therefore, it is important to maintain balance between gravitational-wave studies of BHs in vacuum and electromagnetic studies of BHs that are situated in accretion flows.

Today, on the one hand we have solid dynamical evidence for objects of extraordinary density – objects such as the two-dozen BHs in X-ray binaries and SgrA*. And on the other hand, we have General Relativity which firmly predicts that these objects have undergone complete gravitational collapse. Whether the collapse leads to a Planck-scale singularity or is mediated by quantum effects on a larger scale is at present not a practical concern for astronomers. Our position is rather the following: While keeping an eye on exotic physics, we assume that GR is the correct theory of strong gravity, and we use this venerable theory to interpret our observations of BHs while searching for inconsistencies and contradictions. Meanwhile, we note that there is compelling evidence that stellar-mass BHs in X-ray binaries and the supermassive BH in Sgr A* have event horizons[3], confirming our belief that GR is the correct theory of strong gravity.

Stellar-mass BHs and the measurement of their spin are the subject of this white paper. Twenty-two dynamically-confirmed BHs are now known[2,4,5]. For a catalog of their host binaries and a schematic sketch to scale of most of them, see respectively Table 1 and Figure 1 in ref. 2. Seventeen of these BHs are in transient systems and five are in systems that are persistently X-ray bright (e.g., Cyg X-1). The masses of these BHs range from 5–20$M_{\odot}$ with a typical value of 10$M_{\odot}$. Eighteen are located in the Milky Way, two in the LMC, and two in other local group galaxies.

2. The Measurement of Spin – A Frontier in Black Hole Research

Astrophysical BHs are completely described by the two numbers that specify their mass and spin[6]. BH spin is commonly expressed in terms of the dimensionless quantity $a_* \equiv cJ/GM^2$ with $|a_*| \leq 1$, where M and J are respectively the BH mass and angular momentum. While mass measurements of stellar BHs have been made for decades, the first spin measurements have been achieved only during the past three years[7–14]. Meanwhile, the spin of a supermassive BH has also been measured[15,16].

Knowledge of BH spin is crucial for answering many key questions, for example: (1) Are relativistic jets powered by spin? It is widely speculated that these jets, observed for at least eight BH microquasars and hundreds of AGN, are powered by BH spin via a magnetic Penrose process[17]. With many secure measurements of spin and mass in hand it will be possible to attack the jet/spin/Penrose-process connection in earnest. (2) What role does spin play in powering a gamma-ray burst? For example, a great uncertainty in modeling long GRBs is whether one can arrive at the core-collapse stage with sufficient angular momentum to make a disk around a BH[18]. (3) What constraints can be placed on models of supernovae, BH formation, and BH binary evolution with both mass and spin in hand[19,20]? (4) What distribution of BH spins should LIGO waveform modelers be considering[21]? (5) For supermassive BHs, is the distribution of spins of the merging partners consistent with hierarchical models for their growth[22]?

In this section, we first consider the two techniques that are currently delivering measurements of spin, namely fitting the thermal X-ray continuum and modeling the profile of the Fe K line. Because spin is such a critical parameter it is important to measure it by both methods, as this will arguably provide the best possible check on our results. *Since the continuum-fitting (CF) method cannot be applied to AGN, BH binaries are the crucial common ground where both current methodologies for measuring spin are now being readily applied.* Secondly, we consider a highly promising and independent avenue to spin – high-frequency QPOs. Finally, we examine X-ray polarimetry, which has the potential to secure the measurement of spin via the CF and Fe K methods, while possibly opening a fourth avenue to spin.

2.1. Current Approaches: The X-ray Continuum and the Fe K Line

BH spin is measured by estimating the inner radius of the accretion disk $R_{\rm in}$, which is identified with the radius of the innermost stable circular orbit $R_{\rm ISCO}$ predicted by GR[6]. Strong support for linking $R_{\rm in}$ to $R_{\rm ISCO}$ is provided by decades of empirical evidence that

$R_{\rm in}$ is constant in disk-dominated states of BH binaries[23] and by recent MHD simulations of thin accretion disks[24,25]. $R_{\rm ISCO}/M$ is a monotonic function of a_*, decreasing from $6GM/c^2$ to GM/c^2 as spin increases from $a_* = 0$ to $a_* = 1$ (ref. 6). *This relationship between a_* and $R_{\rm ISCO}$ is the foundation of both the CF and the Fe K methods of measuring spin.*

In the CF method, one determines $R_{\rm ISCO}$ by modeling the X-ray continuum spectrum of the dominant thermal component using KERRBB2 (refs. 9,26), which is an elaboration of the 1973 model of Novikov & Thorne[27]. The observables are X-ray flux, temperature, distance D, inclination i, and BH mass M. In order to obtain reliable values of a_*, it is essential to (1) select X-ray spectra that have a strong thermal component and (2) have accurate estimates of M, i and D, which are typically derived by modeling optical data[4].

The CF method has delivered the spins of six stellar BHs[7–11]. Meanwhile, spins for four more BHs are in the works and a half-dozen more are targeted for future study. Here we highlight results for three BH binaries: M33 X-7 (see Fig. 1), LMC X-1 (see Fig. 2) and GRS 1915+105 (ref. 9). The BH primary of the third system – a microquasar with unique and striking properties – is a near-extreme Kerr BH with a lower limit on its dimensionless spin parameter of $a_* > 0.98$. As illustrated in Figures 7–14 in ref. 9, this result is robust in the sense that it is independent of the details of the data analysis and insensitive to the uncertainties in mass and distance of the BH. A proviso is that one select data of low to moderate luminosity ($L/L_{\rm Edd} < 0.3$), corresponding to accretion disks that are geometrically thin ($H/R < 0.1$).

In the Fe K method, one determines $R_{\rm ISCO}$ by modeling the profile of the broad, skewed line that is formed in the inner disk by Doppler effects, light bending, and gravitational redshift[28]. Of central importance is the effect of the redshift on the red wing of the line. This wing extends to very low energies for a rapidly rotating BH ($a_* \sim 1$) because in this case gas orbits near the event horizon. Relative to the CF method, measuring the extent of this red wing in order to infer a_* is hindered by the faintness of the signal and uncertainties in subtracting the continuum. However, the Fe K method has the virtues that it is independent of M and D, while the blue wing of the line even allows an estimate of i. *What makes the Fe K method enormously important is that it is currently the only viable approach to measuring the spins of supermassive BHs in AGN.* (For further details on the Fe K method, see the white paper by J. Miller et al.).

2.2. High Frequency QPOs and X-ray Polarimetry

High Frequency QPOs – Central Question: What is the correct model of these strong-field X-ray oscillations? Arguably, High Frequency QPOs (HFQPOs; 100–450 Hz) are likely to offer the most reliable and precise measurement of spin once the correct model is known. HFQPOs have been detected in seven BH sources[2]. They are of special interest because their frequencies are in the expected range for matter in orbit near the ISCO. Four of the seven sources exhibit harmonic pairs of frequencies in a 3:2 ratio. These frequencies (single or pairs) do not vary significantly despite sizable changes in X-ray luminosity.

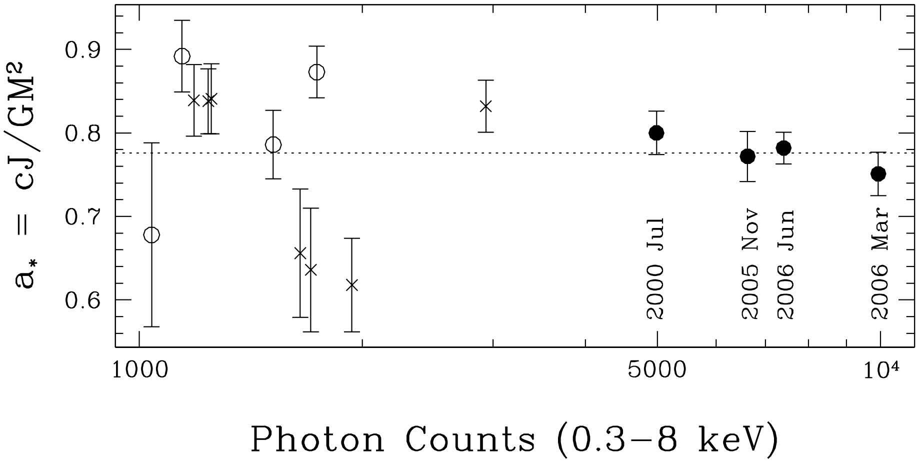

Fig. 1.— Spin results for the BH primary in M33 X-7 obtained by fitting *Chandra* spectra (filled/open circles) and *XMM* spectra (crosses) to the relativistic disk model KERRBB2 (ref. 10); the data are ordered by total counts. The four "gold" *Chandra* spectra with $\gtrsim 5000$ counts each (filled circles) yield spin estimates that agree with the mean value (dotted line) to within their $\approx 2\%$ statistical uncertainties, which is remarkable stability given that the observations span years (see dates). Meanwhile, this mean value agrees with the mean spin for the 11 low-quality spectra with < 3000 counts to within $\approx 1\%$. Including all observational uncertainties (e.g., BH mass), one obtains $a_* = 0.77 \pm 0.05$.

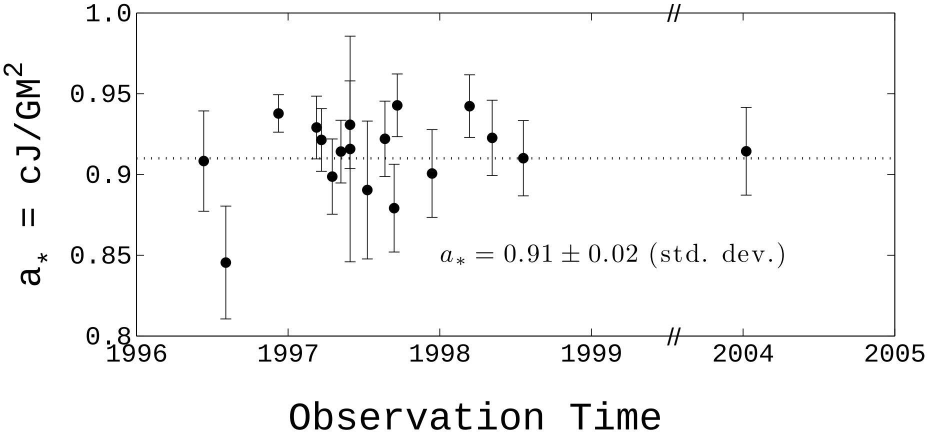

Fig. 2.— Spin results versus time for the BH primary in LMC X-1 obtained by fitting *RXTE* spectra to the relativistic disk model KERRBB2 (ref. 11). The spectra were selected as minimally Comptonized from a complete sample of 55 *RXTE* spectra. As indicated, the scatter about the mean value of a_* is small. Including all model-parameter and observational uncertainties (e.g., α-viscosity and BH mass), one obtains $a_* = 0.90^{+0.04}_{-0.09}$. Virtues of *RXTE* are its good coverage of the Compton power-law component above 10 keV and the many independent observations it provides (typically hundreds); drawbacks are its poor low-energy response and spectral resolution.

Overall, these oscillations appear to be a stable and identifying feature of a BH that are dependent on the mass and spin of the BH. HFQPOs are transient and subtle with typical QPO amplitudes of $\sim 1\%$. The entire sample of HFQPOs detected by *RXTE* at $> 4\sigma$ are illustrated in the white paper by J. Tomsick et al. and in ref. 2. As this figure shows, and as argued by Tomsick et al., these oscillations are near the sensitivity limit of *RXTE* – the only mission to have detected them – and a more powerful timing mission is required in order to explore and exploit them.

X-ray Polarimetry – Central Question: Is the spin of a stellar BH aligned with the orbit vector? If a BH's spin were to be misaligned from the orbit vector, the inner and X-ray-emitting portion of its accretion disk would be warped away from the outer disk[29]. One can measure any misalignment by comparing the orbital inclination angle $i_{\rm orb}$ (routinely measured to a few degrees via optical observations) to the inclination of the inner disk $i_{\rm disk}$. The direct approach to measuring $i_{\rm disk}$ is via polarimetric studies of BH binaries in disk-dominated states[30,31]. The predicted degree of polarization varies from 0% to $\sim 5\%$ as the disk inclination changes from face-on to edge-on. Meanwhile, based on two current mission concepts, even a NASA SMEX-class payload is capable of determining the polarization of the inner disk to an accuracy of 0.1% by observing a typical bright BH binary for about 10 days, thereby constraining the disk inclination to within a degree or two[31].

The CF method of measuring BH spin (§2.1) is straightforward to apply, the required data are readily obtainable, and even the theory of disk accretion in strong gravity is tractable (see §3). However, the method is called into question by a single assumption, namely that $i_{\rm disk} = i_{\rm orb}$. Unfortunately, the CF method cannot fit for $i_{\rm disk}$ and check for disk warp because there is a degeneracy between the inclination and spin parameters[31]. *Therefore, X-ray polarimetry studies are required to validate this key assumption of the CF method.*

The Fe K method of measuring spin (§2.1) will also be greatly strengthened by polarimetric data. These data will check on the inclination estimates obtained via fits to the Fe K line, or allow this parameter to be fixed in the fits. Furthermore, polarimetry can provide qualitatively new information on source geometry and magnetic fields on spatial scales comparable to a BH event horizon[30,31]. This capability promises to be crucial in defining the geometry of the coronal source that powers the Fe K line via fluorescence, a source that is now vaguely and variously characterized as a sphere or a slab or a lamp post.

Finally, we note that it may be possible to determine BH spin solely via polarimetry, thereby securing an additional independent measurement of spin. This possibility is implied by the pioneering work of Connors et al.[32] and has been explored in recent work[30,31].

3. The Required Key Advances in Observation and Theory in Priority Order

An X-ray timing/spectral mission dedicated to the study of bright Galactic sources: Since its launch in late 1995, *RXTE* has revolutionized our knowledge of stellar BHs and neutron stars because of its large area, its high data-rate capabilities, and especially because it is a dedicated observatory that allows sustained, synoptic observations of these complex and variable systems. Additionally, its All-Sky Monitor maintains continual surveillance of the entire sky, which is critically important because 95% of the known Galactic stellar BHs are transient X-ray sources. A new follow-on mission with order-of-magnitude improvements in collecting area, data rate, and spectral resolution – and with sensitivity well below the 3 keV cutoff of *RXTE* – is required in order to make the next step. Such a mission will at once serve the three prime spin methodologies: Briefly, large area is needed for studying HFQPOs and good spectral resolution for resolving the Fe K line, while sensitivity down to $\sim$ 1 keV profits the CF method by capturing the full thermal continuum spectrum. For more on such a mission, see the white paper by Tomsick et al. and ref. 33.

In addition to a dedicated mission, it is crucial that the International X-ray Observatory (IXO) also have the capability to observe bright Galactic BH transients as targets of opportunity. Specifically, the inclusion of the High Time Resolution Spectrometer will insure that no Rosetta-stone transient slips away unobserved.

Advances in computational astrophysics: Both the CF and Fe K methods of measuring BH spin assume that disk radiation cuts off at the ISCO. This is a valid assumption provided that the accreting gas has negligible torque at the ISCO. But does the torque really become small at the ISCO? The only way to find out is by means of 3D MHD simulations of the accreting gas in the Kerr metric of a spinning BH. This nascent area of research is currently poised to take off. Powerful GRMHD codes have been developed and tested[34,35] and have begun to provide the first direct estimates of the stress profile in disks of various thicknesses around non-spinning and spinning BHs[25,36,37]. However, the energy dissipation profile and the corresponding radiative properties of the disk – the most important quantities for applying theoretical models to observations – are still unknown and require much more work. The physics of HFQPOs too is likely to be understood only when GRMHD simulations that include radiation are carried out. These developments require (1) numerical GRMHD codes that can efficiently model thermodynamics and radiation physics and (2) larger computational resources than are presently available. The former can be enabled with adequate funding of theoretical and numerical research and the latter with serious investment in computer hardware.

X-ray polarimetry mission: Most effective would be a modest mission dedicated to observing bright stellar BHs and neutron stars. Either of two instrument concepts developed within the severe constraints of a NASA SMEX-class payload would be quite effective – a photoelectron-track polarimeter or a Bragg-crystal instrument. Either instrument can, for example, detect polarization in a 1 Crab source at the $\sim$ 0.3% level in 1 day, and at the $\sim$ 0.1% level in 10 days[31].

4. Goals: 2010–2020

- Firmly establish the fledgling enterprise of measuring BH spin via the CF and Fe K methods: Obtain precise and accurate values of spin for 10–20 BHs using one of the methods, and for several BHs using both methods.

- Obtain *complete* descriptions of many stellar BHs in order to test models of jets, GRBs, supernovae, BH formation, BH binary evolution, etc.
- Establish the Fe K methodology for application via IXO to supermassive BHs.
- Identify the correct model of HFQPOs and so open a third channel for measuring spin.
- Pursue X-ray polarimetry as a means of securing the continuum-fitting and Fe K methods, and also as a possible fourth avenue to spin.
- Develop and test realistic GRHMD models of thin disks in strong gravity.

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