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Black Hole Spin Measurements via X-ray Continuum Spectroscopy

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A remarkable property of an astrophysical black hole is that it is completely described by just its mass and spin. Our research group is dedicated to measuring these two fundamental properties of the black hole primaries found in X-ray binary systems. We measure spin by modeling the thermal X-ray continuum spectrum that originates in the innermost regions of the accretion disk. We fit for the disk's inner radius, which we identify with the innermost stable circular orbit (ISCO) predicted by GR. By measuring this radius in concert with optical estimates for the black hole mass, orbital inclination angle and distance of the system, we uniquely determine a black hole's spin. I will present an overview of our spin measurements and discuss progress which would be enabled with a large collecting area X-ray timing instrument.

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1. Introduction

Astrophysical black holes are among the most important objects to modern physics. A black hole is that presently mysterious point where quantum mechanics and Einstein's relativity converge. At the same time, a black hole is remarkably simple. The no-hair theorem tells us that a black hole is described by just two numbers: its mass M and spin angular momentum ($J \equiv a_* M^2 G/c$)[1].

By compiling measurements of black-hole spins, we can test the theory that powerful jets are produced via the extraction of spin energy from rapidly rotating black holes (e.g., [2]). Likewise, knowledge of spin can constrain theories of binary evolution and massive supernovae (e.g., [30, 16]) and even allow fundamental tests of both general relativity (e.g., [10]) and string theory [1].

Currently, two means of measuring spin have been broadly developed and implemented for a handful of sources each: the continuum-fitting (CF; [31]) and Fe-$K\alpha$ [6] methods. Combined, these methods have been used to measure the spins of more than a dozen stellar-mass black holes. Both types of spin measurements operate indirectly, taking advantage of the link between the accretion disk's inner edge ($R_{\rm in}$) and the black-hole's spin.

The foundation for this measurement-by-proxy lies in relativistic dynamics: Around the black hole, there is an innermost-stable circular orbit (ISCO), inwards of which orbiting material plummets to the horizon on a dynamical timescale ($\lesssim$ 1ms for a stellar-mass black hole). Classical theory thus predicts that the inner edge of a geometrically thin, optically thick accretion disk will be located at the ISCO. This prediction is borne out by recent general relativistic, magnetohydrodynamic simulations (GRMHD; [11, 20, 25]; but see also [17]). Critically, beyond providing an edge for the accretion disk, general relativity dictates a unique mapping between the dimensionless radius of the ISCO ($R_{\rm ISCO}/M$) and the spin of a black hole (e.g., [27]). This foundation – that the ISCO corresponds to the disk's inner edge, and that $R_{\rm in}$ therefore maps directly to spin – is the basis for both the CF and Fe-$K\alpha$ methods of measuring spin.

The CF method, on which we focus, relies upon modeling thermal multicolor blackbody emission to measure $R_{\rm ISCO}$ and thereby spin. To achieve this, three key elements are necessary: (1) from theory, an emission profile for the accretion disk; (2) from ground-based observations, accurate estimates of mass, inclination and distance; and (3) from X-ray observatories, X-ray spectra, which prominently feature the thermal accretion-disk continuum emission.

1. Relativistic alpha-disk theory, harkening back to Novikov & Thorne (1973), describes the expected thermal spectrum produced by a razor-thin accretion disk about a black hole. Using this theory as a basis, our fully relativistic code, KERRBB2, also includes the effects of limb-darkening, self-irradiation, and spectral hardening [12, 5, 15].

2. The CF approach is analogous to determining the radius of a star of known distance from its observed flux and temperature, except that the system is cylindrical rather than spherical. In this way, it is possible to obtain the radius of the ISCO by measuring the disk flux and characteristic temperature as long as both the distance D to the black hole and its inclination

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[1] The dimensionless spin parameter a_* is bounded between $-1 \leq a_* \leq 1$. In principle, a black hole can have a third parameter, electric charge, but this is unlikely to be important for astronomical black holes.

i are known[2]. Lastly, it is necessary to also know the mass M to convert between $R_{\rm ISCO}/M$ and spin (see above). M, i, and D are generally derived from ground-based photometric and spectroscopic observations.

3. Finally, an X-ray spectrum with a strong disk component is necessary in order to accurately model the thermal continuum and obtain spin. We rely primarily on data taken when the black hole is in the *thermal-dominant* state which is typified by soft disk emission and a comparatively very weak Compton power law [21]. Our only other strong requirement is that the disks we observe are well approximated by the razor-thin accretion disk model we employ. To achieve this, we set a luminosity restriction $L < 0.3\ L_{\rm Edd}$, where $L_{\rm Edd}$ is the Eddington limit [15]. Above this threshold, the disk flares beyond the thin disk limit and enters into a domain which in the near future will be treated by "slim-disk" models (e.g., [23]).

From the last requirement, it is evident that the optimal X-ray facility for this science should provide broad spectral coverage around the thermal peak of bright stellar black holes ($\sim 1-10$ keV), that it should be capable of handling bright Galactic targets (with intensities approaching several Crab), and that the signal should be maximized via a large collecting area. Furthermore, in order to achieve a full synergy between the CF and Fe-$K\alpha$ methods, the facility needs a spectral resolution better than 5-10% and large collecting area around 7 keV.

In contrast to the CF method, the Fe-$K\alpha$ approach uses primarily the Fe-$K\alpha$ lines and other fluorescence features produced in hard spectral states. Spin is obtained by determining $R_{\rm in}/M$ from the degree of relativistic broadening of these spectral features. This method has the advantages of not requiring any knowledge of M or D, and providing its own estimate of i. The relative disadvantages are that the spectral models employed are more complex and that the signal is fainter than from the disk continuum.

For the first time, we have independently applied both methods and found a consistent estimate of spin; this was done for the black hole in XTE J1550–564 [29]. In the following section, we return to – and establish – the foundation for both methods of measuring spin. In Section 3, we give a census of CF spin measurements and highlight our results for XTE J1550–564. The final section centers on the crucial role of the HTRS in measuring spin via both methods.

2. Foundation

The critical assumption underpinning current measurements of black-hole spin is the asserted link between spin and $R_{\rm in}$; namely, the assumption that the accretion disk terminates at the ISCO. Such a relationship naturally results from geometrically thin hydrodynamic accretion flows [18, 26], but can in principle break down when the accretion disk is strongly magnetized or becomes geometrically thick.

We divide our discussion of this assumption into two parts, which will be addressed separately. First, we explore the constancy of the accretion-disk inner radius empirically, letting black-hole

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[2] The inclination used here is generally that of the binary orbital plane. We assume that the black-hole spin axis and orbital angular momentum are in alignment, as predicted for old binary systems (see, e.g., [7] and references therein).

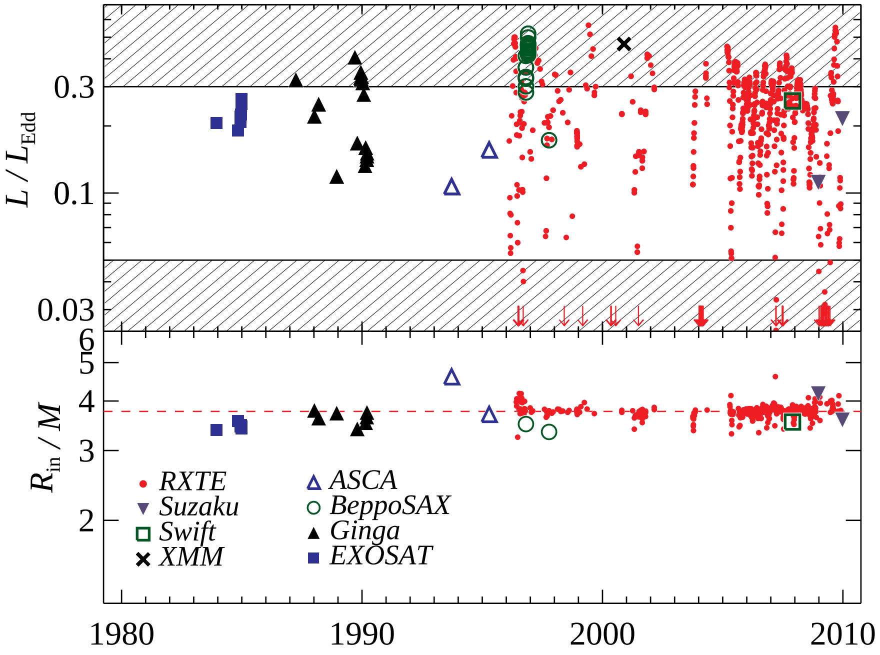

Figure 1: Adapted from [28]. **top:** Accretion-disk luminosity in Eddington-scaled units ($M = 10\ M_\odot$) versus time for all the data considered in that study (766 spectra). Data in the unshaded region satisfy both the thin-disk selection criterion ($L/L_{\rm Edd} < 0.3$) and a lower luminosity threshold of 5% $L_{\rm Edd}$. **bottom:** Values of the inner-disk radius $R_{\rm in}$ are shown for the unshaded data in the top panel (411 spectra). Despite large variations in luminosity, $R_{\rm in}$ is constant to within $\approx$ 4% over time. The median value for the *RXTE* data alone is shown as a red dashed line.

spectra lead the way. Using a collection of hundreds of LMC X–3 spanning several decades, we demonstrate that a remarkably stable inner-radius is observed over a broad range of disk luminosities. Second, we address the validity of the Novikov & Thorne model, in which $R_{\rm in}$ corresponds to $R_{\rm ISCO}$, by turning to GRMHD simulations.

2.1 Constancy of $R_{\rm in}$: The case of LMC X–3

LMC X–3 is a ripe target in our Local Group. Its prime location in the Large Magellanic Cloud, persistent X-ray activity, and soft spectrum make LMC X–3 uniquely capable of providing a strong test of the existence and stability of the ISCO. To achieve this, we have mined the HEASARC archive and extracted all the available data for LMC X–3, an ensemble of data collected by eight different X-ray missions and spanning 26 years. We considered all available data except for those whose flux calibration we considered to be unreliable (e.g., some grating modes).

In the thin-disk regime we consider, and over luminosity variations spanning roughly an order of magnitude, we find for the entire collection of data that the radius is constant over the 26 years to within 4%. The inter-mission consistency in the measured values of $R_{\rm in}$ is just 6%. The data and our results are summarized in Figure 1, which shows both the long-term intensity variation of the source and the stability of the disk's inner radius. This study not only provides evidence for the existence and stability of the accretion-disk inner edge, but it also further strengthens the case for X-ray CF as a viable means of measuring spin by showing that our results are quite insensitive

Black Hole	a_*	Reference
M33 X–7	0.84 ± 0.05	[13, 14]
LMC X–3	0.3[a]	[4]
LMC X–1	$0.92^{+0.04}_{-0.07}$	[9]
A0620–00	0.12 ± 0.18	[8]
4U 1543–47	0.8[a]	[24]
XTE J1550–564	$0.34^{+0.20}_{-0.28}$ [b]	[29]
XTE J1655–40	0.7[a]	[24]
GRS 1915+105	0.99 ± 0.01	[15]

Table 1: Continuum-Fitting Spin Measurements

Errors are 1σ.
[a] Value is provisional.
[b] Using both CF and Fe-$K\alpha$ methods, the jointly-measured spin is 0.49.

to the brightness/temperature of the source and to the choice of the broadband detector used in making the observations.

2.2 The Novikov-Thorne model

The question of the validity of the Novikov-Thorne (NT) model has been most recently addressed by Kulkarni et al. [11], whose work is based on the GRMHD simulations done by [20]. For several values of a_*, Kulkarni et al. use their simulations of thin disks[3] to produce fake X-ray spectra. They then analyze each spectrum with the NT model (i.e., KERRBB2) and compare the derived value of spin with the value used in performing the GRMHD simulation.

The principal outcome of this study is that while systematic differences are present, in all cases the deviations from the NT model are smaller than current observational uncertainties. Furthermore, these deviations decrease as the luminosity decreases and the disk becomes thinner. Thus, Kulkarni et al. have shown that the NT model, while approximate, provides a good description of thin disks and, additionally, that the inner edge of the disk, which above was shown to be stable, is located very near $R_{\rm ISCO}$.

3. Current Results

In Table 1, we summarize our present census of CF black-hole spin measurements. Notably, all the spins are prograde, and the values cover the full range between 0–1. We now discuss our measurements of the spin of XTE J1550–564 using both the CF and Fe-$K\alpha$ methods.

3.1 J1550: a joint CF and Fe-$K\alpha$ study

XTE J1550–564 (hereafter J1550) is a poster-child microquasar system which in 1998 underwent a violent outburst followed by an atypical re-ignition and subsequent decay. During its

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[3] These simulated disks have roughly twice the thickness of the real disks used to measure spin.

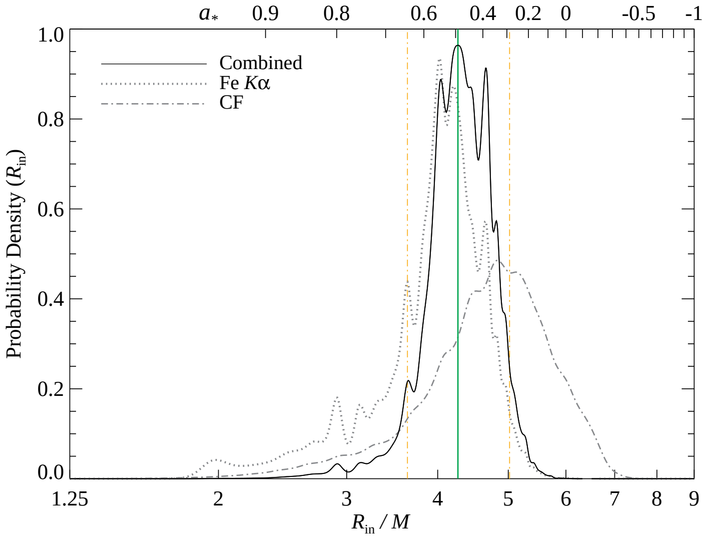

Figure 2: The solid line shows the combined Fe-$K\alpha$ and CF probability density for $R_{\rm in}$ (bottom axis) and a_* (top axis). The net result is a moderate value ($a_* = 0.49^{+0.13}_{-0.20}$, at 90% confidence). This figure is adapted from [29].

outburst, J1550 launched a pair of superluminal jets. These jets were observed several years later in X-rays by Chandra, shocking against the ambient ISM [3], the first discovery of its kind.

Because of the importance of this microquasar, we performed ground-based optical observations and derived new precise estimates for the binary parameters and distance ($M = 9.1 \pm 0.6$ M$_\odot$, $i = 74.7 \pm 3.8$ degrees, $D = 4.4 \pm 0.5$ kpc; [19]). Building on these results, we determined J1550's spin using ~ 50 RXTE spectra. The spin is relatively low, $a_* = 0.34^{+0.20}_{-0.28}$, and a spin above 0.8 is strongly ruled out. We find very high internal consistency between the X-ray measurements ($< 5\%$ spread); our error is instead dominated by the uncertainties in i and D.

In an effort to improve this CF measurement and to check for cross-consistency with the iron line method, our collaborator Rubens Reis independently measured the spin of XTE J1550–564. Using REFBHB, a premier model of spectral reflection in black-hole binaries [22], he obtained $a_* = 0.55^{+0.10}_{-0.15}$ [19]. The two measurements are consistent with a moderate value of spin, namely $a_* = 0.49$. Figure 2 shows probability densities for these two measurements, as well as the combined result.

4. Discussion

Advancing our knowledge of black holes is of critical importance to both physics and astrophysics. X-ray astronomy is uniquely poised to contribute black-hole spin demographics and in fact can provide these measurements via a trio of techniques. In addition to the CF and Fe-$K\alpha$ methods already described, several black holes have shown transient 3:2 high-frequency quasi-periodic oscillations (QPOs) that must originate in the inner disk [21]. It is widely theorized that these QPOs are connected to spin, but the exact link is as-of-yet uncertain.

X-ray measurements of the spins of stellar-mass black holes can therefore be pursued via three independent paths: timing measurements of QPOs, which requires a large collecting area to com-

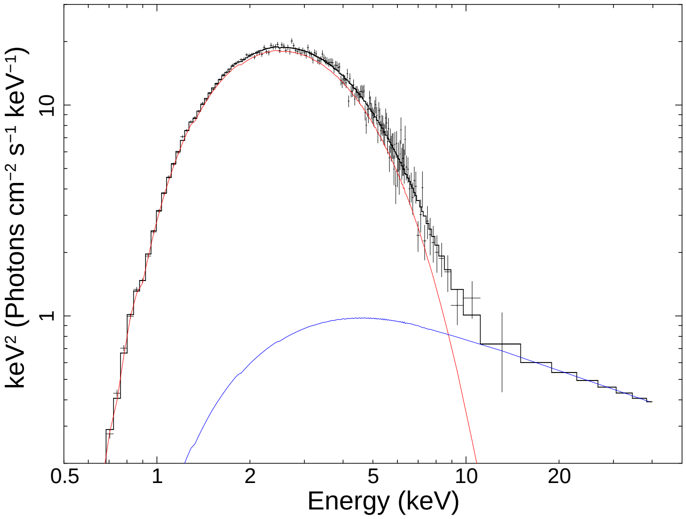

Figure 3: A 1s HTRS simulated observation of a 1-Crab black hole in the thermal-dominant state. The red line shows the underlying disk component, and the blue shows the Compton power law.

pensate for the weakness of the signal; the relativistically broadened Fe-$K\alpha$ line complex, which demands moderate (several-percent) spectral resolution, as well as a large collecting area; and the CF method, for which a broadband spectrum covering $\approx 1-10$ keV is necessary. Remarkably, the HTRS designed for IXO covers all of these bases.

For CF spin measurements, IXO's HTRS importantly provides much more collecting area than the PCA on RXTE, as well as improved low-energy sensitivity, thereby allowing a ~ 100-fold efficiency increase over RXTE for a typical black hole in its thermal state. For example, Figure 2 shows a spectrum produced in the HTRS by a typical 1-Crab black-hole source in *just one second* of observation. High signal-to-noise measurements of the continuum at these short timescales will enable observers to probe down to the viscous timescale in the inner $\approx 10\ R_g$ of the disk, where the bulk of emission originates.

We have only begun to plumb the compared performance of the Fe-$K\alpha$ versus CF methods. Meanwhile, spin measurements of the same stellar-mass black holes made using both approaches is important for establishing each method, and is of particular importance to the Fe-$K\alpha$ method, which is *the* viable approach for measuring the spins of accreting supermassive black holes. The groundwork has been laid. An instrument with the capabilities of the HTRS would enable us to extend our measurements of spin and to further our insight into nature's black holes.

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