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CONSTRAINTS ON BLACK HOLE SPIN FROM X-RAY SPECTROSCOPY

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RESUMEN

Presentamos un nuevo código capaz de modelar líneas de emisión ensanchadas por efectos relativistas en discos de acreción alrededor de agujeros negros. El modelo `kerr` permite que el spin del agujero negro sea un parámetro libre en el ajuste, y el usuario puede así colocar restricciones sobre el momento angular del agujero, así como sobre otros parámetros físicos. Hemos aplicado el modelo `kerr` al espectro entre 2 y 10 keV para la galaxia Seyfert-1 MCG–6-30-15 y encontrado que el parámetro de spin es $a = 0.97 \pm 0.03$ con 90% de confiabilidad, basado en el ancho de la línea Fe-Kα. La degeneración entre varios parámetros del modelo hace que la incertudumbre real sea bastante más grande, pero aún así mostramos que un agujero negro de Schwarzschild está excluido con alta probabilidad, y que el mejor ajuste es para un agujero negro que tiende a tener rotación máxima.

ABSTRACT

We present a new code to model relativistically broadenend emission lines produced from accretion disks around black holes. The `kerr` model allows black hole spin to be a free parameter in the fit, enabling the user to constrain the angular momentum of a black hole as well as several other physical parameters of the accretion disk surrounding it. We have applied the `kerr` model to the $2 - 10\,\mathrm{keV}$ spectrum of the Seyfert-1 galaxy MCG–6-30-15 and have constrained its black hole spin parameter to $a = 0.97 \pm 0.03$ at 90% confidence, based on the breadth of the Fe-Kα feature in this source. Though the degeneracies between various model parameters render the exact value of the spin likely much more uncertain than this, we do show that a Schwarzchild black hole is quite robustly ruled out, and that the data clearly prefer a fit with a black hole that tends toward maximal spin.

Key Words: **BLACK HOLE PHYSICS — GALAXIES: ACTIVE**

1. INTRODUCTION

The inner portions of accretion disks around black holes are the loci of some of the most energetic phenomena in the universe. Magnetic fields connecting the black hole to the disk, general relativity, and the overall angular momentum of the disk-hole system combine to create jet-like outflows, severely warped spectral features, and a host of other high energy signatures of this type of uniquely extreme environment. It is only recently, however, that technology has allowed observers the chance to examine the inner portions of these disks with the spectral resolution necessary to effectively probe general relativitic effects, in particular. Starting with *ASCA*, and with the advent of new, improved orbiting X-ray observatories such as *Chandra*, *XMM-Newton*, and now *Suzaku*, astronomers are now able to examine the spectra of accretion disks in unprecedented detail. Here, we focus on efforts to assess the spin of a black hole using X-ray observations of disk emission lines.

These disk emission lines are thought to be produced as follows: ultraviolet photons emitted by accretion disks around black holes get inverse Compton-scattered by relativistic electrons in a hot coronal plasma surrounding the disk, or perhaps in the base of a jet. Some of these scattered photons (now X-rays) get reflected back down onto the disk and excite a series of fluorescent emission lines. Because the lines produced also have X-ray energies, they are best looked for by instruments with high spectral resolution and throughput, such as *Chandra*, *XMM-Newton*, and *Suzaku*.

The most prominent line of this series is that of Fe-Kα at a rest frame energy of $6.4 - 6.97\,\mathrm{keV}$, depending on its level of ionization. Its strength and location make it one of the few fluorescent disk lines visible above the power law continuum generated by the corona (or base of a jet) which dominates the spectra of both active galactic nuclei and and Galactic black hole candidates at hard energies above $\sim 2\,\mathrm{keV}$.

Most of the emission from the disk is produced fairly close to the event horizon of the BH as material

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loses its gravitational potential energy by falling into the steep potential well. It is also thought that the corona or base of a jet which generates the reflected X-rays is fairly localized around the inner disk. Combining this fact with the effects of gravitational lensing on the reflected radiation means that most of the incident photons are expected to impact the central parts of the accretion disk. This portion of the disk is also where extreme Doppler and relativistic effects become important. Here, the typical Voigt profile of an emission line will be convolved with effects from Doppler shifting, special relativistic beaming and general relativistic gravitational redshifting, resulting in a highly broadened and skewed emission line profile.

Black hole spin also alters the structure of the inner, energetically-dominant region of the disk in several complex ways, one of which is by bringing the radius of marginal stability in the disk (r_{ms}) closer to the event horizon as the angular momentum of the BH increases. BH spin is astrophysically interesting not only because it is thought to be one of the two defining characteristics of a black hole, but also because it is potentially a powerful energy source for the disk, jets, and other forms of particle acceleration in the BH system. In fact, BH spin may well be an important parameter in determining the basic nature of many BH-powered astrophysical sources, such as AGN, GBHCs, and GRBs.

One of the fundamental assumptions about the effect of BH spin on the morphologies of the fluorescent disk emission lines in question is that the line gets broader as the spin of the BH increases, therefore the detection of a broad iron line in a source means that the BH powering it is spinning rapidly. This is not always the case, however, and in fact several groups have recently argued that these disk lines cannot be used as valid diagnostics of BH spin at all, because of the inherent degeneracy in the parameters governing the line morphology (Beckwith & Done 2004; Dovciak et al. 2004). That is, it is possible to construct a broad line with a non-spinning BH by altering several other parameters in the system such as the inner radius of emission within the disk and the disks emissivity profile. While this is indeed true, we argue that these lines profiles can, in fact, be used as viable BH spin diagnostics as long as one takes into account the physical realism of the best-fit parameters governing the BH-disk system. For example, we can synthesize a broad line with a Schwarzchild BH by forcing the inner radius of emission in the disk to lie well within the r_{ms}, such that the majority of the radiation emitted from this region undergoes an enormous gravitational redshift and greatly broadens the red wing of the resulting line profile. As we will show later, however, when fit to real data this condition demands a best-fit disk emissivity index that is unphysically high. So while one must use caution in interpreting the best-fit spin parameter (denoted a, in units of cJ/GM^2) of the BH too literally, we do believe that the morphologies of fluorescent iron lines, in particular, can at least help us viably constrain the spin of the BH.

2. THE KERR MODEL

There are two publicly available models within the XSPEC package (Arnaud 1996) that can be used to fit accretion disk emission lines. The `diskline` model (Fabian et al. 1989) has the spin parameter of the BH hard-wired at $a = 0.0$ (Schwarzchild case). Although all the calculations are done on the fly and both special relativity and Doppler shifting are taken into account, light bending is not, and as such the model is not fully relativistic. The `laor` model (Laor 1991) is fully relativistic, taking light bending into account, and has its spin set to the maximum physical value of $a = 0.998$. Because it was created at a time when computing speeds were not what they are now, however, the values of the photon transfer function have been pre-computed and stored in extensive tables, so the calculations are not done on the fly, and thus because of sampling effects the model lacks accuracy, especially in the red wing of the line profile. Additionally, neither `diskline` nor `laor` take radiation from within the innermost stable circular orbit of the disk into account. Both models also only allow a single disk emissivity index (em $\propto r^{-\alpha}$, where $\alpha = 3$ for a "standard" disk). In reality there is likely a gradient in the emissivity index of the disk with radius, wherein the emissivity index will progressively steepen as one approaches the event horizon, then perhaps either "spike" or turn over, depending on whether magnetic field torquing of the disk by the BH comes into play. So approximating this gradient in emissivity with a single power law index can limit the accuracy of the model fit to the data. Using a broken power law function where the index changes at some "break" radius in the disk provides a slightly more realistic, better fit.

Keeping this in mind, our goal is to create a better publicly available model for these broad disk lines that meets the following conditions:

- Allows BH spin to be a free parameter ($a = 0.0 - 0.998$),
- Enables a broken power law fit to the disk emissivity index,

- Incorporates radiation from within the ISCO.

We have created the `kerr` model within XSPEC to satisfy these conditions, and are currently making final improvements on it with the aim of releasing it in the next version of XSPEC as an installed model. We have based our work primarily on the ray-tracing algorithms of Cunningham (1973, 1975) and Speith (1995), and have employed many of the Speith subroutines, in particular.

`Kerr` will be comparable in result to both the `Ky` model of Dovciak et al. (2004) and the similar model designed by Beckwith & Done (2004). Those models also satisfy our three goals for completeness and are fully relativistic, but at present our model has two main advantages and one disadvantage in comparison. The advantages are that we perform all calculations on the fly without referring to pre-calculated tables of photon transfer function values, and that we will take both optical depth and the ionization profile of the disk material into account when considering emission originating from within the ISCO (this will be incorporated into the final version of the code). The disadvantage is that such thoroughness comes with significant computational expense in XSPEC: for example, a full fit of the $2-10\,\mathrm{keV}$ spectrum of MCG–6-30-15 (using the 350 ks Fabian et al. 2002 *XMM-Newton* data set) with a broad `kerr` line takes several hours on a 2 GHz linux machine. We are currently exploring ways to parallelize the fitting process using several machines in tandem with ISIS software (Houck & Denicola 2000), but this type of parallelization is unfortunately not possible within the XSPEC framework.

3. FITTING THE SPECTRUM OF MCG–6-30-15

An interesting test case for implementing the `kerr` model is the canonical Seyfert-1 galaxy MCG–6-30-15. This object has been thought to harbor a rapidly spinning black hole since the first detection of a broad iron line in its spectrum with *ASCA* (Tanaka et al. 1995; Iwasawa et al. 1996), and this broad feature has since been corroborated by several other observations since then with both *XMM-Newton* and *Chandra* (e.g. Wilms et al. 2001; Lee et al. 2000). Using the *XMM-Newton* data taken by Fabian et al. (2002), we have examined the breadth of the iron line profile and fit the $2-10\,\mathrm{keV}$ spectrum with a model that includes Galactic photoabsorption ($N_{\mathrm{H}} = 4.1 \times 10^{20}\,\mathrm{cm}^{-2}$) and a power law continuum ($\Gamma = 1.91$, $1.39 \times 10^{2}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$) as well as a `kerr` line and two narrow gaussians representing iron lines in different stages of ionization at 6.4 and 6.9 keV. Without the broad `kerr` component or the narrow gaussians, the breadth of the iron feature – especially the red wing – is readily apparent (see Figure 1a). The χ^2/dof for the simple photoabsorbed power law fit is 4577/1106.

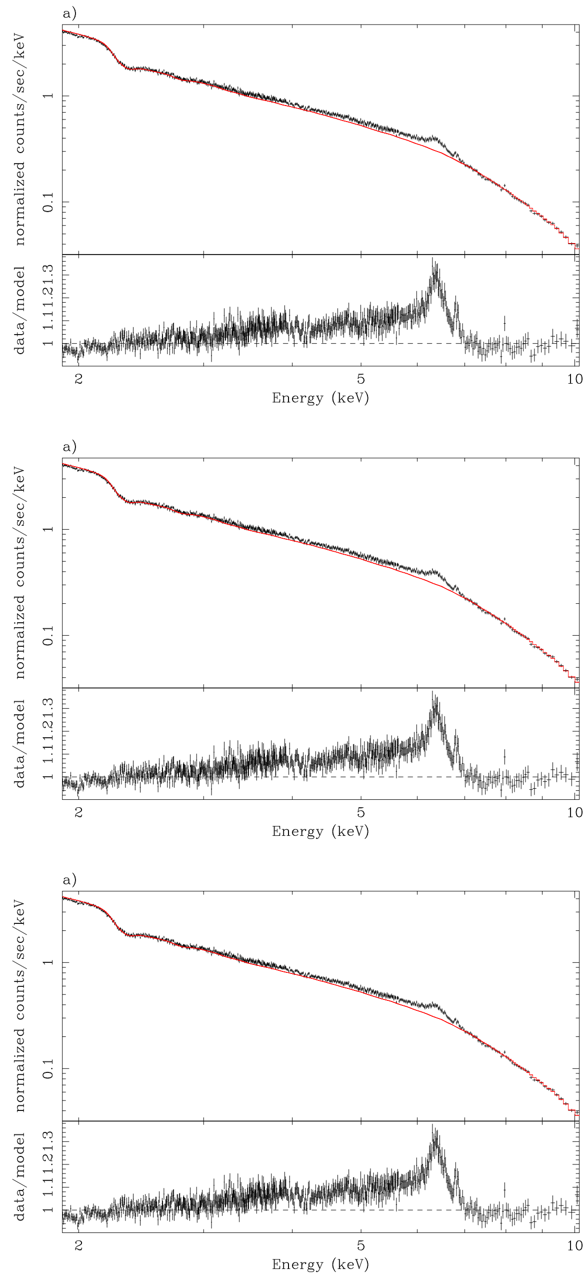

Fig. 1. (a) The `phabs(po)` fit to MCG–6-30-15. Notice the significant deviations of the data from this model, especially around 6.4 keV. (b) A `kerr` line is added to the fit at $\sim 6.4\,\mathrm{keV}$, along with two narrow gaussians at 6.4 and 6.9 keV, with $a = 0.0$ (Schwarzchild case). (c) The best-fit model with a left as a free parameter, arriving at ~ 0.97.

If we try fitting the spectrum with a non-spinning BH profile (i.e. spin parameter frozen at zero in `kerr`), as in Figure 1b, the fit visually looks fairly adequate. $\chi^2/\mathrm{dof} = 1400/1097$, a significant improvement over the simpler fit above. However, closer inspection of the best-fit parameters for such a model reveals that the non-spinning hole scenario demands that the inner emissivity index of the disk be unreasonably steep ($\alpha_1 \approx 8$). This agrees with a similar conclusion reached by Begelman & Reynolds (1997) using the `diskline` model to fit an earlier MCG–6-30-15 data set. Here, the authors also found that the inner emission radius in the disk was forced to be significantly inside r_{ms} ($r_{in} < 4r_g$; $r_{ms} = 6r_g$ for a Schwarzchild BH). These two points also mean that in the Reynolds & Begelman fit, almost all of the emission originates from within r_{ms}. At present we have not yet finished coding emission from within the ISCO into the `kerr` model code, but presumably doing so will yeild a similar result, based on our steep inner disk emissivity index. All of our fits have the inner radius of emission frozen at r_{ms}. So although it is possible to construct a good fit with a Schwarzchild BH, the other physical parameters of the system do not favor the non-spinning case.

Conversely, if we allow the spin parameter to be free and find any value it wants, we lower the value of χ^2/dof for the data set to 960/1096. While the fit does not visually appear much better, we see that once the best-fit spin parameter of $a = 0.97$ is reached, the emissivity profile of the disk also looks much more physically believable: $\alpha_1 = 5.65$, $\alpha_2 = 2.86$. The best-fit values for the `kerr` model parameters are shown in Table 1. Error bars are quoted at 90% confidence. Additionally, plots of the change in χ^2 with a are shown in Figures 2a-b, illustrating that the best fit clearly tends toward maximal BH spin.

We should note again that for these fits, the inner emission radius of the disk has been frozen at r_{ms}, so emission from within the ISCO is not included. We are still working on finalizing and testing this portion of the code. However, the red wing of the iron line in this source is already so broad that incorporating this emission within the ISCO would likely have little effect on the overall fit we have presented, and would not alter our conclusion that MCG–6-30-15 harbors a near maximally-spinning BH.

4. CONCLUSIONS AND FUTURE WORK

We have created the a new model within XSPEC, called `kerr`, which synthesizes fluorescent emission lines produced in the accretion disks surrounding black holes. Our model differs from the two publicly available models (`diskline` and `laor`) in that it is fully relativistic and performs all calculations on the fly, and allows for the spin of the BH to be a free parameter. Additionally, we incorporate emission from within the ISCO and enable the disk emissivity index to be modeled with greater precision as a broken power law. While our model is comparable to the new models of both Dovciak et al. (2004) and Beckwith & Done (2004), we do not pre-calculate values of the photon transfer function, and we intend to take the optical depth and ionization level of the disk material within the ISCO into account in the final version of the code when evaluating the effects of emission from this region on the line profile.

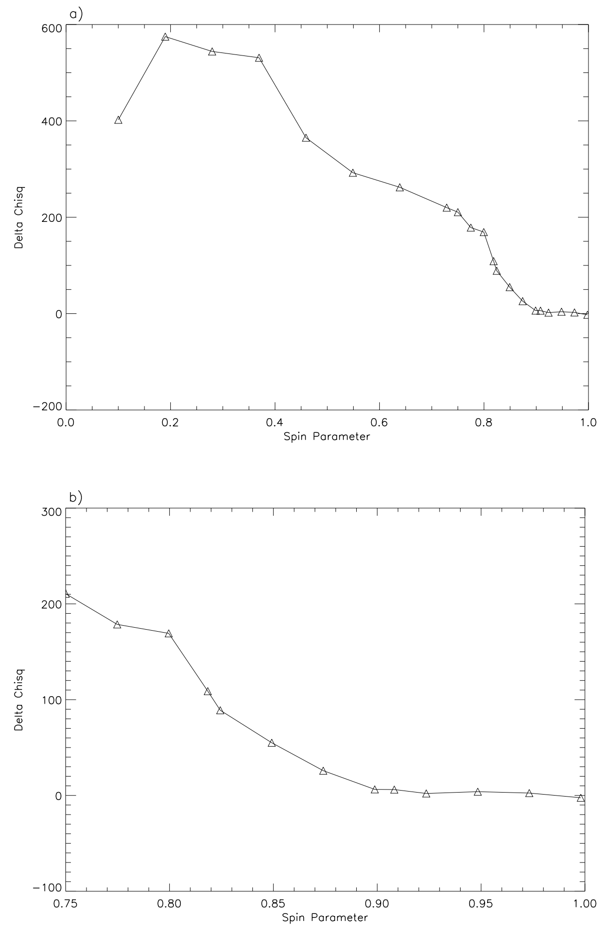

Fig. 2. (a) $\Delta\chi^2$ vs. a for the best-fit model to MCG–6-30-15. The overall shape of the plot strongly suggests that near-maximal BH spin is preferred by the data. (b) The same plot, zoomed in to examine the region from $a = 0.75 - 0.998$ more closely. The minimum was found to be $a = 0.97 \pm 0.03$ at 90% confidence.

TABLE 1

BEST-FIT PARAMETERS FOR THE 2 − 10 keV SPECTRUM OF MCG–6-30-15

Model Component	Parameter	Value
phabs	$N_{\mathrm{H}}(\,\mathrm{cm}^{-2}\,)$	0.041
po	Γ	1.903 ± 0.007
	flux ($\mathrm{ph\,cm^{-2}\,s^{-1}}$)	$1.363 \pm 0.01 \times 10^{-2}$
kerr	lineE (keV)	6.576 ± 0.039
	α_1	5.652 ± 0.629
	α_2	2.863 ± 0.151
	r_{br} (r_g)	5.747 ± 0.82
	a	0.970 ± 0.03
	i (°)	20.40 ± 2.236
	r_{in} (r_g)	1.738
	r_{out} (r_g)	113.26 ± 1.692
	z	0.008
	flux ($\mathrm{ph\,cm^{-2}\,s^{-1}}$)	$2.980 \pm 0.259 \times 10^{-4}$
zgauss	lineE (keV)	6.4
	σ (keV)	10^{-3}
	z	0.008
	flux ($\mathrm{ph\,cm^{-2}\,s^{-1}}$)	$9.104 \pm 4.226 \times 10^{-6}$
zgauss	lineE (keV)	6.9
	σ (keV)	10^{-3}
	z	0.008
	flux ($\mathrm{ph\,cm^{-2}\,s^{-1}}$)	$8.352 \pm 3.186 \times 10^{-6}$

Values for the Galactic hydrogen column density and both line energies of the narrow gaussians added were frozen at the values originally determined in Fabian et al. (2002). The widths of the gaussian lines were frozen at 10^{-3} keV for simplicity, keeping them at a standard "narrow" value. All redshifts were frozen at the cosmological value for MCG–6-30-15: $z = 0.008$. Error bars are calculated at 90% confidence.

In fitting the hard spectrum of MCG–6-30-15 with the kerr model, we have shown that the data prefer a fit with a spin parameter that tends towards the maximum value. A non-spinning BH can produce a visually adequate fit (although still statistically worse than that achieved with a free spin parameter), but further examination of the effect this condition has on the emissivity profile of the disk shows that the fit achieved in this case is not physically reasonable. Both Dovciak et al. (2004) and Beckwith & Done (2004) make valid points about the difficulty of accurately calculating the spin parameter of a BH based on broad line profiles from the disk alone. Given the number of parameters governing the kerr line profile (nine, to be exact), some degeneracy between them is certainly to be expected, and it is possible to generate statistically indistinguishable line profiles using different combinations of parameters. This does not render the use of broad lines as spin diagnostics obsolete, however: provided that one uses care in determining whether parameter values are physically reasonable, it is possible to at least constrain the spin parameter to be within a certain range of values. In the example of MCG–6-30-15 above, we have clearly shown that the data do not prefer a non-spinning BH if we also demand that the values for the disk emissivity indices are physically realistic. The plots of $\Delta\chi^2$ vs. a clearly show the improvement in fit achieved when one frees the spin parameter: the fit strongly tends toward maximal spin.

In finalizing the model and preparing it for public release, we are currently testing the robustness of the photon transfer function calculations within the

ISCO, as well as exploring ways to tie optical depth and ionization tables describing the state of the gas within the ISCO to the transfer function computations. We hope to have a final version of the code incorporating these effects by early 2006.

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