Continua and Iron-K Lines from Accreting Black Holes

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Abstract

A fair fraction of Galactic stellar-mass black holes are reported to be rapidly spinning, based on their broad Fe-K lines. However, such broad features couple strongly with the spectral continuum, and cause the modeling to degenerate. By carefully analyzing broad-band *Suzaku* data, and also employing the information on optically-thick disk emission, GX 339−4 is inferred to harbor a low-spin black hole. In addition, the *Suzaku* spectra of the Seyfert galaxy MCG-6-30-15 are interpreted in an alternative way, without invoking the rapid black-hole spin.

Key words: black holes: continua — black holes: iron lines — black hole: disk inner radii

1. Introduction

A mass-accreting black hole (BH) is characterized by its mass $M_{\rm BH}$, accretion rate, inclination i, and the spin parameter, a^*. Among them, a^* is the observationally least constrained, yet theoretically important, parameter. We may estimate a^* by measuring iron line profiles, which become broader and more skewed due to stronger relativistic effects as a^* increases (*e.g.*, Fabian et al. 1989). This is mainly because the radius of innermost stable circular orbit (ISCO) changes form $6R_{\rm g}$ for $a^*=0$ (non-spinning) down to $1.24R_{\rm g}$ for $a^* \to 1$ (maximally rotating), where $R_{\rm g} \equiv GM_{\rm BH}/c^2$ is the gravitational radius.

The wide-band *Suzaku* observation of the Seyfert galaxy MCG–6-30-15 in fact gave $a^* > 0.917$ (Miniutti et al. 2007). In addition, a fair number of black-hole binaries (BHBs) are reported to have similarly high values of a^* (Miller 2007; Miller et al. 2009). However, the claimed Fe-K lines are so broad, that their profiles couple strongly with the continuum determination. Here, we critically review the issue.

2. Lessons from Cyg X-1

The *Suzaku* observations of Cyg X-1 (Makishima et al. 2008) have yielded a number of important implications. In Fig. 1, we show its spectral ratios against those of GRO J1655−30 (Takahashi et al. 2008), both obtained with *Suzaku* in the Low-Hard State (LHS). From this figure alone, we can derive some important inferences.

1. Since the absorbing column is similar between the two, the low-energy rise of the ratio is due to a higher visibility of the disk emission in Cyg X-1. This is partially caused by their inclination difference ($i \sim 45^\circ$ for Cyg X-1 and $i \sim 70^\circ$ for the other).
2. A moderately broad Fe-K line feature is seen. This results from a stronger line of Cyg X-1, which in turn is probably due to the inclination difference. However, the ratios do not show any extremely broad Fe-K line component: it would be unlikely that such features in the two spectra cancel out by chance.
3. Nowhere in the 1 $\sim$ 100 keV range, the ratios exhibit a simple power-law (PL) shape. Therefore, the continuum of either (or both) object should deviate from a pure PL. This applies to the the 2–4 keV range which is used in the Fe-K line modeling.

A relativistic modeling of the Fe-K line in Cyg X-1 gave the innermost radius of line-emitting region as $R_{\rm Fe} \sim 15R_{\rm g}$, in agreement with Miller et al. (2009). Considering Comptonization of the disk photons, the inner radius of the optically thick disk was also estimated as $R_{\rm in} \sim 15R_{\rm g}$. Thus, we confirm $R_{\rm Fe} \sim R_{\rm Fe}$, and conclude that the disk in the LHS does not reach the ISCO.

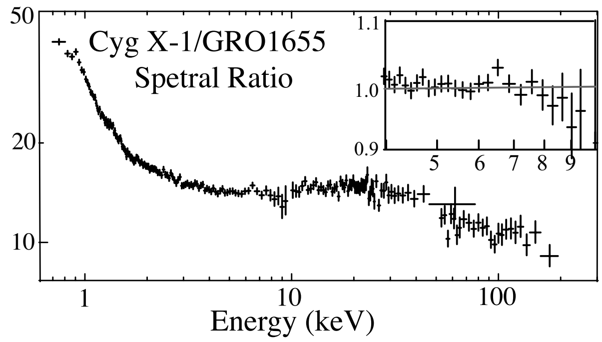

Fig. 1. Ratios between the *Suzaku* spectra of Cyg X-1 and GRO J1655−30 (from Makishima et al. 2008 and Takahashi et al. 2008). The inset shows a zoom up of the 4–10 keV region.

3. Problems with Continuum Modeling

As revealed by Fig. 1 and Makishima et al. (2008), continua of BHBs, which underly the Fe-K line region, may be too complex to be expressed by a single PL plus a simple multi-color disk (MCD; Mitsuda et al. 1984) model. This poses a difficulty, when trying to quantify broad line features that are only a few percent level above the continuum. When a simple continuum plus a narrow line model leaves broad *negative* residuals around the Fe-K line, we know that the continuum model is wrong. However, if broad *positive* residuals are seen, we cannot readily tell whether they are real or caused by a wrong continuum. Such a degeneracy occurs when, *e.g.*, the continuum has multiple PL slopes (like in Cyg X-1); or the disk emission is slightly Comptonized; or the modeling of disk reflection is inappropriate; or the emission is partially covered by an absorber.

As a simple exercise of the 2nd case above, let us consider a model spectrum of Fig. 2a, which emulates a BHB spectum in the Very High state. After Kubota & Makishima (2004), the continuum is composed of a single PL with a photon index $\Gamma = 2.62$ (thin solid line), and a Comptonized blackbody (`compbb`) with a temperature of 0.51 keV. The Comptonizing electron temperature is assumed to be 20 keV, and the optical depth as $\tau = 0.38$. After Cyg X-1, we add a `laor` Fe-K line, with $R_{\rm Fe} = 15R_{\rm g}$ and an emissivity index $q = 3$.

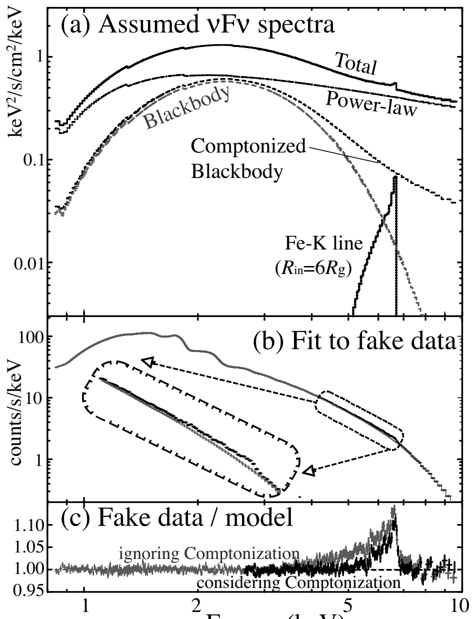

Fig. 2. An exercise of false broadening of the Fe-K line. (a) A $\nu F \nu$ form of the assumed model, which consists of a PL, a Comptonized BB, and a moderately broad Fe-K line. (b) A simulated XIS spectrum (gray), fitted with a BB+PL model without considering the Comptonization. (c) Ratios of the simulated data to the model, which does (black) and does not (gray) consider the disk Comptonization.

Figure 2b shows the simulated *Suzaku* XIS spectrum based on the above model. By fitting it with the same `compbb+PL` continuum, but ignoring the 4–7 keV range, the data to model ratio becomes as shown in Fig. 2c in black; the assumed Fe-K profile is restored all right. However, if we force $\tau = 0$ and readjust the other parameters, the ratio falsely exhibits a much broadened Fe-K wing (Fig. 2c gray). As a confirmation, we fitted the entire spectrum by a `compbb+PL+laor` model with $\tau = 0$. In this successful ($\chi^2_{\rm r} = 1.18$ for $\nu = 425$) fit, the `laor` inner radius became $R_{\rm Fe}/R_{\rm g} = 1.78^{+0.21}_{-0.34}$. The Compton tail in the disk emission has been mistaken for a broad Fe-K line wing, leading to a false measurement of a^*.

4. The Case of GX 339−4

Using *XMM-Newton* and *Suzaku* data, Miller et al. (2004, 2008) claimed that the Fe-K line of GX 339-4 is extremely broad, and hence this BHB hosts a maximally rotating BH with $R_{\rm Fe} \sim R_{\rm g}$. However, reanalyzing the *Suzaku* data, Yamada et al. (2010) found that the XIS data utilized by Miller et al. (2008) suffer strong event pile up, which distorts the continuum shape and indirectly affects the Fe-K line profile.

Even putting aside the pile up issue, the Fe-K line profile depends considerably on the continuum as shown in Fig. 3. There, the background-subtracted data from the XIS (pile-up uncorrected) and HXD-PIN are shown divided by two sets of MCD+PL models. When $\Gamma = 2.2$ is used as Miller et al. (2008) did, the Fe-K line profile (grey) appears very broad, but the continuum becomes too hard to explain the HXD-PIN data. When $\Gamma = 2.44$ is chosen and the model parameters are readjusted (black), the continuum matches the HXD-PIN data, leaving a room for reflection, and the Fe-K line profile becomes much narrower. In reality, the PL slope should be even steeper, when the piled up XIS events are discarded (Yamada et al. 2010). This exemplifies how the continuum modeling affects the Fe-K line shape.

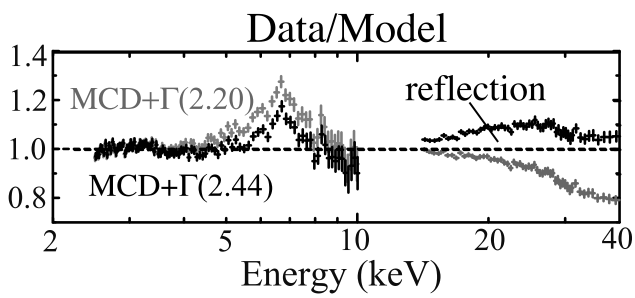

Fig. 3. The *Suzaku* XIS and HXD-PIN spectra of GX 339−4, normalized to two sets of MCD+PL models with different parameters (neither optimized). The XIS data are accumulated over $0' - 4'$, where the pile up effects are severe. This figure is similar to Fig. 3 of Yamada et al. (2010), except that the HXD-PIN data are included here with its cross normalization adjusted arbitrarily.

Yamada et al. (2010) performed a full reanalysis of the *Suzaku* XIS, HXD-PIN, and HXD-GSO data of GX 339−4, discarding central regions of the XIS image to avoid the pile up. Figure 4 shows the fit goodness as a function of $R_{\rm Fe}/R_{\rm g}$, referring to an absorbed `disk+PL+pexriv+laor` model where `disk` is some disk emission model and `pexriv` represents reflection from an ionized medium. When the central $2'$ is excluded and the disk emission is represented by an MCD model, the best-fit is found at $R_{\rm Fe}/R_{\rm g} < 3.5$ (open circles) in agreement with Miller et al. (2008). However, when the MCD is replaced by a `compbb`, the results become umbiguous (grey squares), due to another chi-square minimum at $R_{\rm Fe}/R_{\rm g} \sim 10$. Finally, an analysis using again an MCD model, and the XIS spectrum from $r > 3'$, favors the $R_{\rm Fe}/R_{\rm g} \sim 10$ solution (filled circles), *i.e.*, a non-spinning BH. Thus, we cannot draw a definite conclusion on a^*. What we can say for sure is that all the models indicate $R_{\rm Fe}/R_{\rm g} < 15$; namely, the line *is* broad.

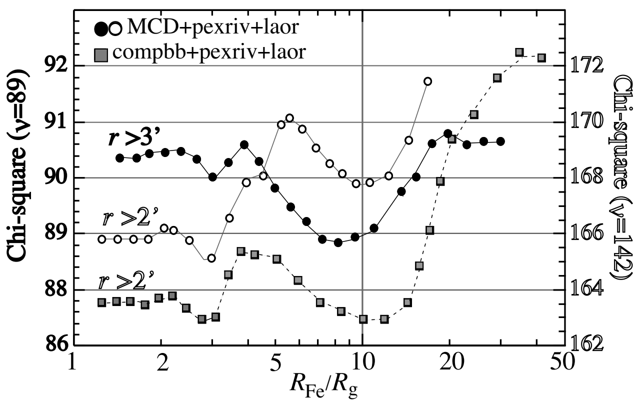

Fig. 4. Goodness of the joint fit to the XIS, PIN, and GSO spectra of GX 339−4, shown as a function of the `laor` inner disk radius $R_{\rm Fe}$. Open and filled symbols are for the XIS spectrum from $r > 2'$ (ordinate on the right) and $r > 3'$ (on the left), respectively. Models are given in the figure top (Yamada et al. 2010).

5. Information from the Disk Emission

Since the Fe-K line profile is often subject to model degeneracies (§3, §4), we vitally need to incorporate some independent methods of spin determination. One viable way is to quantify the emission form optically-thick accretion disks, using, *e.g.*, a simple MCD method, and estimate its inner radius $R_{\rm in}$. Then, on condition that the source distance, inclination, and the BH mass are known with reasonable accuracy, we can estimate the $R_{\rm in}/R_{\rm g}$ ratio which is sensitive to a^*. Its application to Cyg X-1 was already mentioned in §2. Similarly, Yamada et al. (2010) obtained $R_{\rm in}/R_{\rm g} = 5 - 32$ from the *Suzaku* data of GX 339−4; this agrees with the filled circles in Fig. 4, and reinforce the view that the BH in GX 339−4 is spinning only weakly (if any).

Admittedly, these $R_{\rm in}$ results on Cyg X-1 and GX 339−4 are somewhat fragile, because the disk emission is relatively weak in both cases, and we had to consider disk photons that are Comptonized into the PL. In contrast, a much unambiguous results was obtained in a *Tenma* observation of GX 339−4 (Makishima et al. 1986), made previously in a typical High/Soft state where the disk emission dominated the signals below 10 keV. As re-phrased in Yamada et al. (2010), the *Tenma* data yielded $R_{\rm in}/R_{\rm g} = 2.8 - 11.2$, considering the distance and mass uncertainties. This agrees well with the *Suzaku* estimates on $R_{\rm Fe}/R_{\rm g}$ and $R_{\rm in}/R_{\rm g}$ described above. Therefore, we regard the BH in GX 339−4 as only weakly spinning, in contrast to Miller et al. (2008).

Even if the accretion disk can be regarded as a standard one, the MCD model (Mitsuda et al. 1984), we admit, gives only an approximation to its integrated emission, with various inherent incompleteness. It ignores all the special/general relativistic effects, neglects zero-torque inner boundary condition, and assumes that the color temperature is equal to the effective temperature. To reduce such incompleteness, we have developed a simple method to empirically correct the MCD-determined values of $R_{\rm in}$ for some of these effects (Kubota et al. 1998; Makishima et al. 2000). In short, we multiply raw values of $R_{\rm in}$ by a factor of 1.18, which is a combination of a color hardening factor 1.7 (Shimura & Takahara 1995), and a correction factor 0.41 for the inner boundary condition; $1.7^2 \times 0.41 = 1.18$.

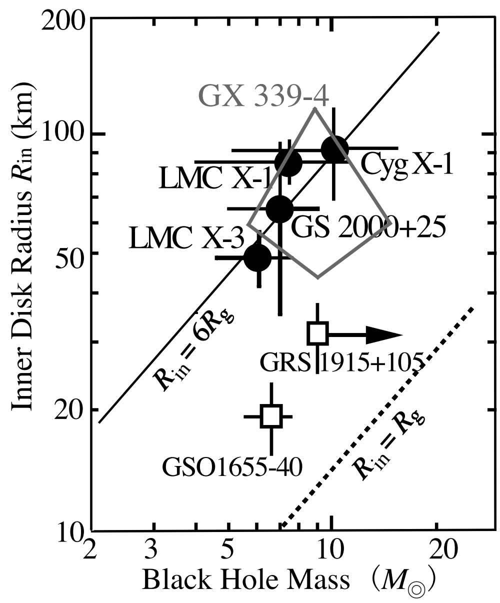

Fig. 5. Values of $R_{\rm in}$ of some BHBs derived from the MCD fit (using the correction factor of 1.18), compared with their BH masses estimated via optical kinematics of the companions. Adapted from Makishima et al. (2000). The information on GX 339−4 has been added.

Tools used in any measurement need *calibration.* This is particularly the case when the MCD method is used to measure $R_{\rm in}$ (§4), because the above correction factor of 1.18 may appear too arbitrary and hence unwarranted. Fortunately, a good calibration has been provided by Fig. 5 (Makishima et al. 2000), where we plot the X-ray measured $R_{\rm in}$ (after multiplied by 1.18) of several BHBs against their BH masses estimated from optical kinematics of their companions. Thus, the four objects with filled circles are consistent with the condition of $R_{\rm in}/R_{\rm g} = 6$ (non-spinning BHs). The case of GX 339−4 (grey trapezoid), based on the *Tenma* result (Makishima et al. 1986), is similar. In contrast, two micro-quasares, GRO J1655−40 and GRS 1915+105, exhibit significantly smaller $R_{\rm in}$ suggestive of larger a^*.

Figure 5 thus imply that the MCD method is reliable to a reasonable accuracy. At the same time, it suggests that significantly non-zero values of a^* may be found only in the two micro-quasares among the sample of 7 BHBs. More quantitative results will be obtained by employing more sophisticated disk emission models that consider general relativistic effects and inner boundary conditions (*e.g.,* Dovčiak et al. 2004; Shafee et al. 2008).

6. Remarks on Seyfert galaxies

Now that we need to be cautious about the "braod" Fe-K lines in BHBs, how about the same features in Seyfert galaxies, first detected with *ASCA* from MCG-6-30-15 (Tanaka et al. 1995), and then from a fair fraction of Seyfert galaxies with, *e.g.*, *XMM-Newton*? As detailed in Miniutti et al. (2007), the broad Fe-K line scenario of MCG-6-30-15 is based on a detailed modeling of disk reflection, and the idea of general relativistic light bending. In addition, it invokes two more implicit assumptions. One is that the underlying continuum is modeled by a single power-law, while the other is that the spectral bump in the 20–40 keV range is due solely to the reflection by the accretion disk. The former condition may change if we consider partial absorption and/or ionized absorbers (Miller, Turner & Reeves 2009).

To examine the nature of the hard bump, we analyzed time variations of MCG-6-30-15 using the *Suzaku* data. As detailed in Noda et al. (2010), we found that the HXD-PIN count rate correlates globally with that of the XIS, but deviates, on a time scale of 10 ksec, from that correlation by $\sim \pm 30\%$. The hard X-ray variation is hence partially uncorrelated with that of the power-law. Similar behavior was observed with *Suzaku* from other Seyferts, including NGC 3516 and Mkn 509. This effect may be interpreted by invoking; (i) contributions from some reflectors other than the disk, or (ii) a fine-tuned motion of the illuminating hard X-ray source invoked in the light-bending scenario, or (iii) the presence of an unknown hard X-ray component that mimics the reflection.

To distinguish the above alternatives, we accumulated the XIS and HXD-PIN spectra over two time intervals, when the HXD-PIN count rate is *higher* and *lower* than the XIS-based prediction. Their "difference" spectrum is very hard, and is approximated by a power-law with $\Gamma \sim 1$ (Noda et al. 2010). Although it resembles in shape the reflection component, the difference spectrum appears to bear neither the prominent Fe-K edge nor the Fe-K line. Therefore, (iii) above is considered most likely. It can be fitted by a thermal Comptonization (`comptt`) with an electron temperature of ~ 10 keV and a rather large optical depth of ~ 20. It could represent a part of the Comptonized power-law continuum, which may consists of multiple optical depths as indicated in § 1.

Finally, we fitted the time-averaged XIS and HXD spectra of MCG-6-30-15 by a combination of a power-law, a reflection, a moderately broad Fe-K line , and the above `comptt`, all subjected to a common absorption. The obtained fit is as good as that with the model by Miniutti et al. (2007), and the reflector solid angle became $\Omega \sim 2\pi$. Furthermore, the equivalent width of the narrow Fe-K line, ~ 120 eV, is consistent with the value of Ω. This means that the *Suzaku* spectra of MCG-6-30-15 can be interpreted consistently without invoking the extreme BH spin, on condition that a fraction of the hard bump is unrelated to the usual reflection signal.

The author would like to express his deepest thanks to Shin'ya Yamada, Hiromitsu Takahashi, Yuich Uehara, Hirofumi Noda, Poshak Gandhi, and other collaborators for their helps and supports.

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