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X-ray observations of black-hole accretion disks ☆

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Abstract

Our current theoretical and observational understandings of the accretion disks around Galactic black-holes are reviewed. Historically, a simple phenomenological accretion disk model has been used to interpret X-ray observations. Although such a phenomenological interpretation is still useful, high quality X-ray data from contemporary instruments allow us to test more realistic accretion disk models. In a simple and ideal case, the standard optically thick accretion disk model is successful to explain observations, such that the inner disk radius is constant at three times the Schwarzschild radius over large luminosity variations. However, when disk luminosity is close to or exceeds the Eddington luminosity, the standard disk model breaks, and we have to consider the "slim disk" solution in which radial energy advection is dominant. Recent observations of Ultra-luminous X-ray sources (ULXs), which may not be explained by the standard disk model, strongly suggest the slim disk solution. We compare theoretical X-ray spectra from the slim disk with observed X-ray spectra of ULXs. We have found that the slim disk model is successful to explain ULX spectra, in terms of the massive stellar black-holes with several tens of solar mass and the super-Eddington mass accretion rates. In order to explain the large luminosities ($>10^{40}$ ergs s^{-1}) of ULXs, "intermediate black-holes" ($>100M_\odot$) are not required. Slim disks around massive stellar black-holes of up to several tens of solar mass would naturally explain the observed properties of ULXs.

Keywords: Black hole accretion disk; X-ray observations; Astrophysics

1. Introduction

It is well-known that the Galactic black-hole binaries indicate bimodal spectral states, so-called high state and low state, according to the 2–10 keV luminosities. In the high state, the X-ray energy spectrum is characterized with soft thermal spectrum and a steep (photon index $\sim$2.5) power-law tail above $\sim$10 keV. In the low state, the energy spectrum is characterized with a flat power-law (photon index $\sim$1.7) and a thermal cut-off at $\sim$100 keV. Bolometric luminosity to divide the high state and soft state may not be clearly defined, because of the hysteresis (Zdziarski and Gierliński, 2004).

The low-state spectrum is explained by thermal Comptonization of soft disk photons ($\sim$0.1 keV) by hot ($\sim$100 keV), thermal plasma. On the other hand, the soft component in the high state is considered to be thermal emission from optically thick accretion disk around the black-hole. In this paper, we concentrate on the study of optically thick accretion disk in the soft state.

2. Standard accretion disk model

In the standard accretion disk model (Shakura and Sunyaev, 1973), all of the gravitational energy released in the optically thick and geometrically thin disk is converted to the thermal energy. In the simplest form, the disk spectrum is represented with superposition of the blackbody spectrum from each isothermal ring, such that temperature dependence on the radius is $T \propto r^{-3/4}(1 - \sqrt{r_{\rm in}/r})$, where $r_{\rm in}$ is the innermost radius. The disk energy spectrum does

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not depend on the viscous parameter α, but solely on the black-hole mass and mass accretion rate. To compare with observation, it is convenient to define the apparent inner disk radius R_{in} and temperature T_{in}, such that the disk emission is superposition of the multicolor rings of the temperature $T(r) = T_{in}(r/R_{in})^{-3/4}$. Using this "multicolor disk model" (Mitsuda et al., 1984), observed disk spectra may be represented with only two free parameters, T_{in} and R_{in}. To estimate the realistic disk parameters from observed T_{in} and R_{in}, inner boundary condition and deviation of the local emission from blackbody emission have to be taken into account (e.g., see Kubota et al., 1998).

Comptonization is significant in the inner part of the accretion disk, because the disk temperature is hot enough (Shakura and Sunyaev, 1973). Local energy spectra from inner parts of the standard accretion disk have been calculated by several authors (e.g., Shimura and Takahara, 1995; Ross and Fabian, 1996; Davis et al., 2005). Basically, these authors agree that the local disk spectrum is approximated with "diluted blackbody" such that the color temperature is higher than the effective temperature by 1.7–1.9 (hardening factor, f), and the flux is diluted by f^{-4}. Importantly, the hardening factor does not change significantly with disk radius and luminosity. Consequently, simple multicolor disk model approximation works, such that the maximum effective disk temperature is T_{in}/f and the realistic innermost disk radius is $r_{in} = f^2 R_{in}$.

Observationally, in the high state of black-hole binaries, the multicolor model inner radius is almost constant regardless of large luminosity changes (Tanaka, 1989; Ebisawa et al., 1993; Gierliński and Done, 2004). This observational fact suggests that the disk innermost radius is determined by mass of the black-hole. In fact, if the constant innermost radius is assumed to be three Schwarzschild radii, the last stable orbit, the black-hole mass constrained from the X-ray disk spectral modeling agree well with fiducial mass determined from binary motion (Ebisawa et al., 1993). Thus, the standard accretion disk model is very successful to explain the X-ray energy spectra of high state black-hole binaries.

3. Relativistic effects

Special and general relativistic effects distort the optically thick accretion disk spectra. In the case of the Schwarzschild black-hole, the innermost disk radius is at the three Schwarzschild black-hole, and introducing the relativistic effects do not significantly alter the black-hole parameters estimated from the Newtonian model (Ebisawa et al., 1991). On the other hand, in the Kerr black-hole case, the innermost disk radius can be smaller, down to half the Schwarzschild radius in the extreme case. The innermost radius is rotating almost at the light velocity, thus the relativistic beaming is enormous. Consequently, inclination dependence of the Kerr disk is extremely large, such that the disk flux in the highest spectral range is *enhanced* in the inclined disk than in the case of face-on disk (e.g., Asaoka, 1989; Laor et al., 1990; Ebisawa et al., 2003).

This unusual behavior of the inclined Kerr disk presumably explains the unusually hard disk spectra of Galactic micro-quasars GRS 1915 + 105 and GRO J1655–40 (Gierliński et al., 2001; Zhang et al., 1997; Makishima et al., 2000; Ebisawa et al., 2003). These two micro-quasars are known to be highly inclined systems and to have very high disk temperature ($T_{in} \sim 2$ keV). Such a high disk temperature is inconsistent with their black-hole mass ($\sim 7M_\odot$ and $\sim 14M_\odot$, respectively), since the maximum apparent disk temperature achievable at the Eddington luminosity in the case of Schwarzschild disk is $T_{in} \sim 1.0$–1.3 $(M/7M_\odot)^{-1/4}$, depending on the inclination angle (higher for inclined disk). If we apply Schwarzschild disk model to these micro-quasars, we end up with unusually small black-hole mass, whereas Kerr disk model with known black-hole mass and moderate spin can nicely explain the observed X-ray energy spectra (Gierliński et al., 1991; Ebisawa et al., 2003). Detection of very fast QPO (~450 Hz) from GRO J1655–40 (Strohmayer, 2001) which may not be explained in the Schwarzschild black-hole (Abramowicz and Kluźniak, 2001) also supports the idea of fast rotating black-holes in micro-quasars.

4. Slim disk model

As the mass accretion increases in optically thick disk, radial energy advection becomes non-negligible. When the disk luminosity is equal to, or exceeds the Eddington luminosity, the advection dominates the accretion flow. Such optically thick advection dominated accretion flow (ADAF), or *slim disk* model was theoretically predicted (Abramowicz et al., 1988).

Several observational consequences are predicted from the slim disk as oppose to the standard disk: (1) slim disk luminosity can exceed the Eddington luminosity at least by factor of several (e.g., Kato et al., 1998), (2) limit-cycle oscillation is expected between the slim disk state and standard state (e.g., Abramowicz et al., 1988; Honma et al., 1991), (3) innermost radius can be close to black-hole than three Schwarzschild radii even in the case of Schwarzschild black-hole, so that the disk temperature gets higher than the standard disk (Watarai et al., 2000), and (4) exponent of the radial dependence of the disk temperature (p in $T(r) \propto r^{-p}$) becomes smaller than the standard value 0.75, down to 0.5 in the extreme case (Watarai et al., 2000).

5. Slim disk in galactic black-hole binaries

In fact, the slim disk seems to be observed in Galactic black-hole binaries when they are extremely bright. The high state X-ray spectra of the black-hole binary XTE J1550–564 are always fitted with multicolor disk model plus power-law tail, *except* when the luminosity and disk temperature are extremely high (Kubota and Makishima, 2004). When the disk luminosity is high and the luminosity is near the Eddington limit, the multicolor disk model does not fit the data, but if the exponent p is made a free parameter, the fit is better with $p \sim 0.5$–0.7, as predicted by the slim disk model.

Another hint of presence of the slim disk model is disk oscillation in GRS1915 + 105. This source is known to have a rapid oscillation of the disk component when the luminosity is near the maximum (see Done et al., 2004 and reference therein), while hard-tail component is rather stable. Such a oscillation is in fact expected as a limit-cycle oscillation between the slim disk state and the standard disk state (Honma et al., 1991). In fact, if we compare the disk spectra at the top of the oscillation and those at the bottom, and apply the "p-free" disk model, the exponent p at the bottom is consistent with 0.75, as expected from the standard disk, while that at the top is closer to 0.5, suggesting the slim disk state (Yamaoka, 2001).

6. Slim disk in Ultra-luminous X-ray sources

Ultra-luminous X-ray sources (ULXs) in nearby galaxies have typical X-ray luminosities from 10^{39} to 10^{41} erg s^{-1}. Since their luminosities are ~100 times higher than the Eddington luminosity of a neutron star, ULXs are suggested to be either super-Eddington sources or intermediate mass black-holes. Most ULXs X-ray energy spectra are fitted with multicolor disk model, but the disk temperature is unusually high ($T_{\rm in} > \sim$1.5 keV; Makishima et al., 2000), if they are standard accretion disk from $\sim 100 M_\odot$ black-hole; in this case $T_{\rm in} \sim 0.5$ keV is expected for Schwarzschild black-hole shining at the Eddington luminosity.

Based on the theoretical basis of slim disk and observational evidence of its existence in the bright Galactic black-hole binaries, it is rather natural to assume that the slim disk state exists in ULXs (Watarai et al., 2001). Observationally, unlike the case of Galactic black-hole binaries (where $R_{\rm in}$ is constant over luminosity variations), $T_{\rm in}$ and $R_{\rm in}$ show anti-correlation for ULX spectral variation (Mizuno et al., 2001). Such a spectral variation may not be explained in the framework of standard accretion disk model, but explained well with the slim disk model (Mizuno et al., 2001; Watarai et al., 2001; Ebisawa et al., 2003).

We compare the spectral model fit of a ULX with the standard disk model and the slim disk model (Fig. 1). We use XMM archival data of NGC 1313 X-2 (observed on October 17, 2000; OBS_ID = 0106860101). Left is the standard disk model fit in the Schwarzschild metric (Ebisawa et al., 1991, 2003). Distance is 3.7 Mpc, and face-on is assumed. The spectral hardening factor (see Section 2) is assumed to be constant at 1.7. We obtain $M = 12.0 M_\odot$, $\dot{M} = 2.1 \times 10^{19}$ g s^{-1}. Bolometric disk luminosity is $0.057\dot{M}c^2 = 1.1 \times 10^{39}$ erg s^{-1}. We can see an obvious hard-tail in the residual (reduced $\chi^2 = 2.5$ for dof = 239). In the right, we show model fit with the slim disk model in Kawaguchi (2003) (face-on assumed). In Kawaguchi (2003), several different types of the slim disk model are calculated. We took the one with $\alpha = 0.1$ and the local emission is modified blackbody (electron scattering is

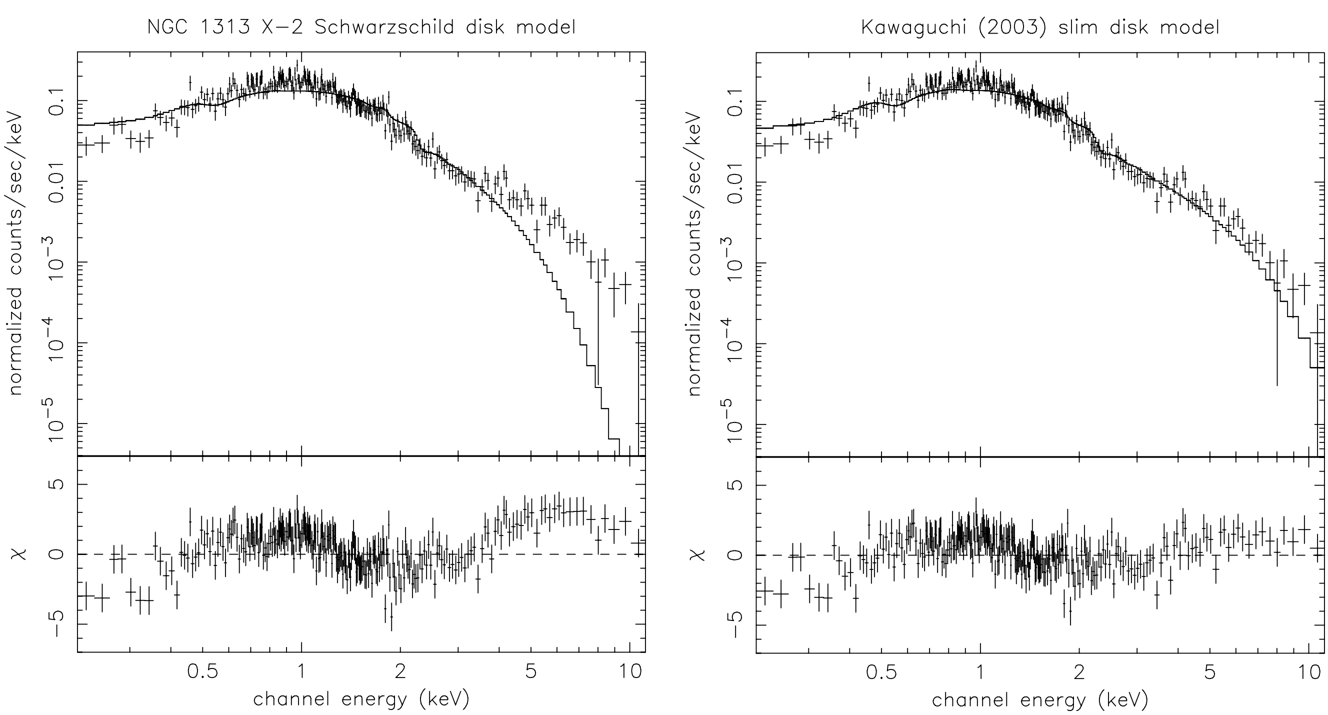

Fig. 1. Accretion disk model fit for NGC 1313 X-2 (XMM pn spectrum). Observation was made on October 17, 2000. Left is the standard disk model in Schwarzschild metric (GRAD model; Ebisawa et al., 1991, 2003). Right is a slim disk model (Kawaguchi, 2003).

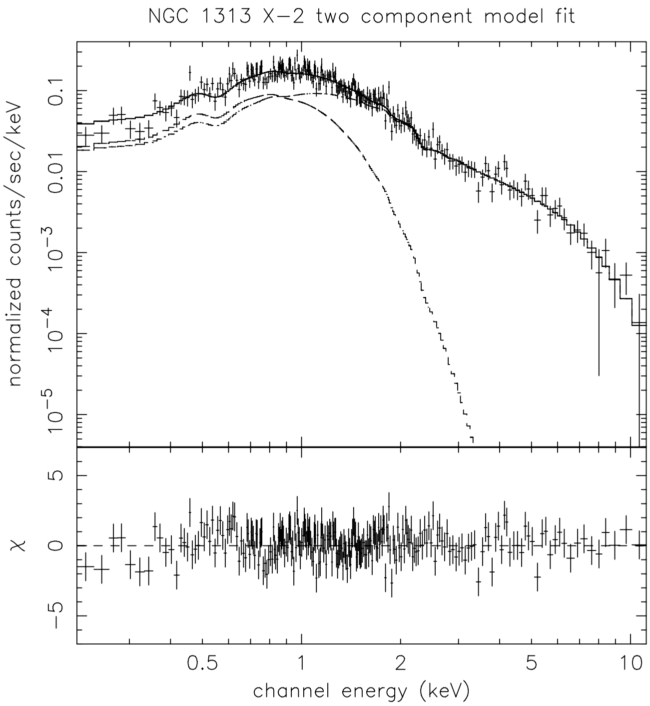

Fig. 2. NGC 1313 X-2 spectral fit with two component model. Almost all the emission above ∼2 keV is fitted with a power-law, and the soft excess is fitted with the standard accretion disk model (GRAD model).

considered, but not energy boost via Comptonization). We obtain $M = 18.6 M_\odot$, $\dot{M} = 4.0 \times 10^{19}$ g s^{-1} (reduced $\chi^2 = 1.7$ for dof = 239). We can see that the hard-tail is modeled reasonably well by the slim disk model, that is because (1) the slim disk can be hotter with smaller innermost radius than the standard disk, and (2) the radial exponent p is smaller than 0.75 so that the area emitting with the maximum temperature is larger than the standard disk. We consider these slim disk model parameters are reasonable for massive stellar black-hole shining at around the Eddington luminosity.

Alternatively, the same spectrum may be fitted with a two component model, such that the hard-tail is explained by an power-law, and soft excess is fitted by the standard accretion disk model (Fig. 2). In this model, the power-law photon index is 2.17, $M = 208 M_\odot$, $\dot{M} = 3.1 \times 10^{19}$ erg s^{-1} (reduced $\chi^2 = 1.1$ for dof = 237). This is basically the same model as Miller et al. (2003) on the same source. Note that we obtain much larger mass of the central object compared to the case of the single component slim disk model fit, since the disk component has such a low temperature.

Having two more free parameters, such a disk + power-law component model fits X-ray energy spectra of other ULXs too. However, besides that the χ^2 is better, we do not have an evidence that ULX energy spectra are composed of two separate components. In the case of Galactic black-hole binaries, presence of the thermal disk component and the power-law hard-tail is obvious, since they vary independently (Tanaka, 1989; Ebisawa et al., 1993). From time to time, we observe *only* the soft disk component in the energy spectra of bright Galactic black-hole binaries, or, variation of *only* the hard-tail component keeping the soft component invariable. In the case of ULXs, on the other hand, we have never seen the base soft disk component *only*. Therefore, we are tempted to conclude that the two component model fit for ULXs does not have a solid physical basis, just mimicking the moderately hard disk spectrum (but softer than power-law), that is more naturally expected from the slim disk model.

7. Origin of Ultra-luminous X-ray sources

We have shown that the NGC 1313 X-2 energy spectrum is described by the slim disk model around a $\sim 19 M_\odot$ black-hole. Similarly from the slim disk model fitting, we have estimated mass of the central object in IC342 Source 1 as $\sim 20 M_\odot$ (Ebisawa et al., 2003). Such massive stellar black-holes have never been found in the Milky-way, but not prohibited by standard stellar evolution theory. There is a universal luminosity function of X-ray binaries (Grimm et al., 2003), which extends toward the highest luminosity $\sim 10^{40}$ erg s^{-1} without break. Presumably, ULXs are population of the brightest X-ray binaries with most massive stellar black-holes. In our model, ULXs are accretion black-holes with a few tens of solar masses shining with super-Eddington luminosities. We do not require "intermediate" mass black-holes ($> 100 M_\odot$) which may not be explained via standard stellar evolution.

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References

Abramowicz, M.A., Czerny, B., Lasota, J.P., et al. Slim accretion disks. ApJ 332, 646–658, 1988.
Abramowicz, M.A., Kluźniak, W. A precise determination of black hole spin in GRO J1655-40. A&A 374, L19–L20, 2001.
Asaoka, I. X-ray spectra at infinity from a relativistic accretion disk around a Kerr black hole. PASJ 41, 763–778, 1989.
Davis, S.W., Blaes, O.M., Hubeny, I., et al. Relativistic accretion disk models of high-state black hole X-ray binary spectra. ApJ 621, 372–387, 2005.
Done, C., Wardziński, G., Gierliński, M. GRS 1915 + 105: the brightest Galactic black hole. MNRAS 349, 393–403, 2004.
Ebisawa, K., Mitsuda, K., Hanawa, T. Application of a general relativistic accretion disk model to LMC X-1, LMC X-3, X1608- 522, and X1636-536. ApJ 367, 213–220, 1991.
Ebisawa, K., Makino, F., Mitsuda, K., et al. Spectral variations of LMC X-3 observed with GINGA. ApJ 403, 684–689, 1993.
Ebisawa, K., Życki, P., Kubota, A., et al. Accretion disk spectra of ultraluminous X-ray sources in nearby spiral galaxies and Galactic superluminal jet sources. ApJ 597, 780–797, 2003.
Gierliński, M., Maciolek-Niedźwiecki, A., Ebisawa, K. Application of a relativistic accretion disc model to X-ray spectra of LMC X-1 and GRO J1655-40. MNRAS 325, 1253–1265, 2001.
Gierliński, M., Done, C. Black hole accretion discs: reality confronts theory. MNRAS 347, 885–894, 2004.

Grimm, H.J., Gilfanov, M., Sunyaev, R. High-mass X-ray binaries as a star formation rate indicator in distant galaxies. MNRAS 339, 793–809, 2003.

Honma, F., Kato, S., Matsumoto, R. Nonlinear oscillations of thermally unstable slim accretion disks around a neutron star or a black hole. PASJ 43, 147–168, 1991.

Kato, S., Fukue, J., Mineshige, S. Black-Hole Accretion Disks. Kyoto University Press, Kyoto, 1998.

Kawaguchi, T. Comptonization in super-Eddington accretion flow and growth timescale of supermassive black holes. ApJ 593, 69–84, 2003.

Kubota, A., Tanaka, Y., Makishima, K., et al. Evidence for a black hole in the X-ray transient GRS 1009-45. PASJ 50, 667–673, 1998.

Kubota, A., Makishima, K. The three spectral regimes found in the stellar black hole XTE J1550-564 in its high/soft state. ApJ 601, 428–438, 2004.

Laor, A., Netzer, H., Piran, T. Massive thin accretion discs. II – polarization. MNRAS 242, 560–569, 1990.

Makishima, K., Kubota, A., Mizuno, T., et al. The nature of ultraluminous compact X-ray sources in nearby spiral galaxies. ApJ 535, 632–643, 2000.

Mitsuda, K., Inoue, H., Koyama, K., et al. Energy spectra of low-mass binary X-ray sources observed from TENMA. PASJ 36, 741–759, 1984.

Miller, J.M., Fabianno, G., Miller, M.C., et al. X-ray spectroscopic evidence for intermediate-mass black holes: cool accretion disks in two ultraluminous X-ray sources. ApJ 585, L37–L40, 2003.

Mizuno, T., Kubota, A., Makishima, K. Spectral variability of ultraluminous compact X-ray sources in nearby spiral galaxies. ApJ 554, 1282–1289, 2001.

Ross, R.R., Fabian, A.C. The spectra of accretion discs in low-mass X-ray binaries. MNRAS 281, 637–643, 1996.

Shakura, N.I., Sunyaev, R.A. Black holes in binary systems. Observational appearance. A&A 24, 337–355, 1973.

Shimura, T., Takahara, F. On the spectral hardening factor of the X-ray emission from accretion disks in black hole candidates. ApJ 445, 780–788, 1995.

Strohmayer, T.E. Discovery of a 450 HZ Quasi-periodic oscillation from the Microquasar GRO J1655-40 with the Rossi X-ray timing explorer. ApJ 552, L49–L53, 2001.

Tanaka, Y. in: Hunt, J., Battrick (Eds.), Proc. 23rd ESLAB Simp. (Bologna) ESA SP-296, Noordwijk, The Netherlands, pp. 3–13, 1989.

Watarai, K., Fukue, J., Takeuchi, M., et al. Galactic black-hole candidates shining at the Eddington luminosity. PASJ 52, 133–141, 2000.

Watarai, K., Mizuno, T., Mineshige, S. Slim-disk model for ultraluminous X-ray sources. ApJ 549, L77–L80, 2001.

Yamaoka, K. Doctoral Thesis, University of Tokyo, 2001.

Zdziarski, A.A., Gierliński, M. Radiative processes, spectral states and variability of black-hole binaries. Prog. Theor. Phys. Suppl 155, 99–119, 2004.

Zhang, S.N., Cui, W., Chen, W. Black hole spin in X-ray binaries: observational consequences. ApJ 482, L155–L158, 1997.