

## Accretion Disk Spectra of the Ultra-luminous X-ray Sources in Nearby Spiral Galaxies and Galactic Superluminal Jet Sources

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**Abstract** Ultra-luminous Compact X-ray Sources (ULXs) in nearby spiral galaxies and Galactic superluminal jet sources share the common spectral characteristic that they have unusually high disk temperatures which cannot be explained in the framework of the standard optically thick accretion disk in the Schwarzschild metric. On the other hand, the standard accretion disk around the Kerr black hole might explain the observed high disk temperature, as the inner radius of the Kerr disk gets smaller and the disk temperature can be consequently higher. However, we point out that the observable Kerr disk spectra becomes significantly harder than Schwarzschild disk spectra *only when* the disk is highly inclined. This is because the emission from the innermost part of the accretion disk is Doppler-boosted for an edge-on Kerr disk, while hardly seen for a face-on disk. The Galactic superluminal jet sources are known to be highly inclined systems, thus their energy spectra may be explained with the standard Kerr disk with known black hole masses. For ULXs, on the other hand, the standard Kerr disk model seems implausible, since it is highly unlikely that their accretion disks are preferentially inclined, and, if edge-on Kerr disk model is applied, the black hole mass becomes unreasonably large ( $\geq 300 M_{\odot}$ ). Instead, the slim disk (advection dominated optically thick disk) model is likely to explain the observed super-Eddington luminosities, hard energy spectra, and spectral variations of ULXs. We suggest that ULXs are accreting black holes with a few tens of solar mass, which is not unexpected from the standard stellar evolution scenario, and that their X-ray emission is from the slim disk shining at super-Eddington luminosities.

**Key words:** superluminal jet sources: ultra-luminous X-ray sources – accretion disks, slim disks – Schwarzschild black holes, Kerr black holes

## 1 INTRODUCTION

Ultra-luminous compact X-ray sources (ULXs) have been found in nearby spiral Galaxies, with typical 0.5 – 10 keV luminosities  $10^{39}$  to  $10^{40}$  erg s $^{-1}$  (e.g., Fabbiano 1988; Colbert and Mushotzky 1999; Makishima et al. 2000; Colbert and Ptak 2002; Foschini et al. 2002). These luminosities are too small for AGNs, and most ULXs are in fact located significantly far from the photometric center of the galaxies. On the other hand, ULXs are too luminous to be considered as the same class of the compact binary X-ray sources in our Galaxy whose luminosities are almost always  $\leq 10^{39}$  erg s $^{-1}$ .

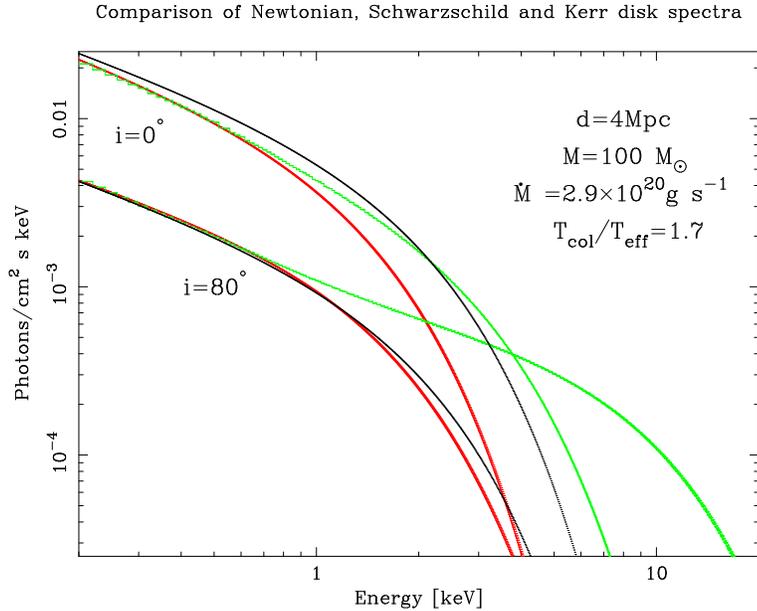
Significant time variations have been detected from ULXs, and their energy spectra are successfully modeled with emission from optically thick accretion disks (Okada et al. 1998; Mizuno et al. 1999; Kotoku et al. 2000; Makishima et al. 2000; Mizuno, Kubota and Makishima 2001), as is the case for the “High” state (= Soft-state) of Galactic black hole candidates (e.g., Tanaka and Lewin 1995). In addition, discovery of bimodal-type spectral transitions (Kubota et al. 2001) and orbital modulations (Bauer et al. 2001; Sugiho et al. 2001) from several ULXs further demonstrate their resemblance with Galactic black hole candidates. These observational facts suggest that ULXs are moderately massive black holes, which may be scale-up versions of the Galactic black holes. So that the observed luminosities of ULXs,  $\sim 10^{40}$  erg s $^{-1}$ , do not exceed the Eddington limit  $L_{\text{Edd}} = 1.5 \times 10^{38} (M/M_{\odot})$  erg s $^{-1}$ , the black hole mass has to be as large as or greater than  $\sim 100 M_{\odot}$ , assuming isotropic emission. How to create such “intermediate” mass black holes, if truly exist, is an intriguing question (e.g., Ebisuzaki et al. 2001). On the other hand, if X-ray emission is unisotropic, the black hole mass is not required to be so large. For example, a beaming model for ULXs has been proposed (King et al. 2001; Körding, Falcke and Markoff 2002); however, presence of a bright nebula surrounding M81 X-9 (Wang 2002) suggests that the nebula is powered by the central X-ray source and that strong X-ray beaming is rather unlikely. Another possibility to solve the super-Eddington problem through unisotropic emission is a geometrically thick accretion disk (Watarai, Mizuno and Mineshige 2001), which we favorably consider later (section 3.1).

GRS 1915+105 and GRO J1655–40 are the two well-known Galactic superluminal jet sources and established black hole binaries with reliable mass measurements ( $M = 6.3 \pm 0.5 M_{\odot}$  for GRO J1655–40 [Green, Bailyn and Orosz 2003] and  $\approx 14 M_{\odot}$  for GRS 1915+40 [Greiner, Cuby and McCaughrean 2001]). If soft X-ray energy spectra of these sources are fitted with an optically thick accretion disk model, their characteristic disk temperatures are  $\sim 1.3 - 2.0$  keV (e.g., Belloni et al. 1997; Zhang et al. 1997; Zhang, Cui and Chen 1997; Tomsick et al. 1999). These values are systematically higher than those of ordinary and well-studied soft-state black hole candidates such as Cyg X-1 and LMC X-3, whose disk temperatures are almost always less than  $\sim 1$  keV (e.g., Tanaka and Lewin 1995).

Okada et al. (1998) found that a luminous ULX in IC 342 ( $\sim 2 \times 10^{40}$  erg s $^{-1}$ ; “Source 1”) has unusually high disk temperature ( $\sim 1.7$  keV), which is similar to the accretion disk spectra of Galactic superluminal jet sources, and pointed out that such a high disk temperature cannot be explained in the framework of the “standard” accretion disk around a Schwarzschild black hole (see section 2.2). The “standard” disk denotes the situation that all the gravitational energy release is converted to thermal radiation, in contrast to the “slim” disk which is an optically and geometrically thick disk with dominant energy advection (section 3.1). Makishima et al. (2000) summarized ASCA observations of seven ULXs, and concluded that the unusually high accretion disk temperature is a common spectral property of ULXs. King and Puchnarewicz (2003) pointed out that ULXs, as well as ultrasoft AGNs, violate the apparent blackbody-temperature and luminosity relationship which is required not to exceed the Eddington limit.

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**Fig. 1** Comparison of Newtonian (black), Schwarzschild (red) and extreme Kerr ( $a = 0.998$ ; green) disk spectra for the face-on ( $i = 0^\circ$ ) and a near edge-on disk ( $i = 80^\circ$ ). Inner disk radius is  $6 r_g$  for the Newtonian and Schwarzschild disks, and  $1.24 r_g$  for the Kerr disk. The same mass accretion rate is assumed, which is so chosen to give the Eddington luminosity for the Schwarzschild disk. Other disk parameters are indicated in the figure. Note that the total disk luminosities are different for the three disk models because the energy conversion efficiencies are different (0.083, 0.057 and 0.366 for Newtonian, Schwarzschild and Kerr disks, respectively).

Zhang, Cui and Chen (1997) and Makishima et al. (2000) suggested that the unusually high disk temperature of the Galactic superluminal jet sources and ULXs may be explained if they harbor fast rotating black holes, since inner edge of the accretion disk gets closer to the black hole in the Kerr geometry and the disk can be hotter. On the other hand, Watarai et al. (2000) and Watarai, Mizuno and Mineshige (2001) proposed that, instead of the standard disk, the slim disk model may explain the X-ray energy spectra of Galactic superluminal jet sources and ULXs.

In this paper, we focus on the “too-hot disk” problem of ULXs and Galactic superluminal jet sources. We apply standard accretion disk models in Newtonian, Schwarzschild, and Kerr cases, and discuss how the relativistic effects and the disk inclination affect the black hole mass and the mass accretion rates obtained from the model fitting. We see that observed hard spectra of Galactic superluminal jet sources may be explained by strong relativistic effects in the highly inclined standard Kerr accretion disk. On the other hand, the hard spectra and the super-Eddington problem of ULXs are difficult to explain in the framework of the standard accretion disk model. We see that the slim disk model may explain the observed super-Eddington luminosities and hard energy spectra of ULXs more naturally.

## 2 APPLICATION OF THE STANDARD DISK MODEL

In Fig.1, we show standard accretion disk spectra (Shakura and Sunyaev 1973) calculated for Newtonian, Schwarzschild, and Kerr metrics. We apply these standard accretion disk spectral models to ASCA archival data of GRO J1655–40 and IC 342 Source 1. The observations were made on 1995 August for GRO J1655–40 (when the source is in a bright state) and 1993 September for IC 342 Source 1 (when the source is in the “high” state; Kubota et al. 2001; Kubota, Done and Makishima 2003). These datasets may be considered “exemplary”, so that the same spectral data of GRO J1655–40 have been analyzed in Zhang et al. (1997), Zhang et al. (2000) and Gierliński, Maciołek-Niedźwiecki and Ebisawa, K. (2001), and those of IC 342 Source1 in Okada et al. (1998), Mizuno et al. (1999), Watarai, Mizuno and Mineshige (2001) and Kubota et al. (2001).

We assume the diluted blackbody local spectra with  $T_{\text{col}}/T_{\text{eff}} = 1.7$ , where  $T_{\text{col}}$  and  $T_{\text{eff}}$  are local color temperature and effective temperature respectively. Difference among the Newtonian, Schwarzschild, and Kerr disk models are only the relativistic effects, including the variation of the innermost radius and energy conversion efficiency. The Schwarzschild disk model we use (GRAD model) is explained in Hanawa (1989) and Ebisawa, Mitsuda and Hanawa (1991). The GRAD model is available in the XSPEC spectral fitting package, and this model also provides the Newtonian disk spectra we use in this paper, when the relativistic switch is turned off.

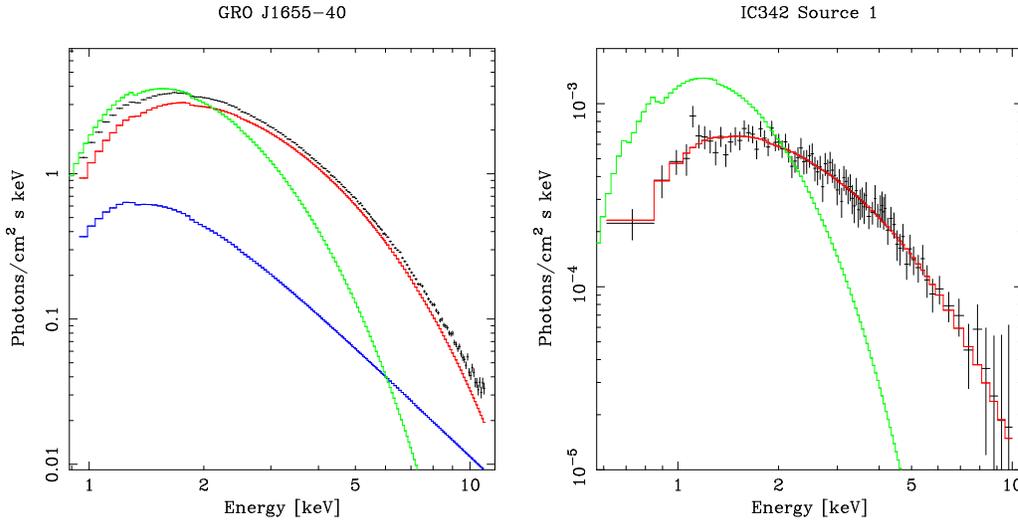
### 2.1 Application to GRO J1655–40

We carry out spectral fitting of the ASCA GIS spectra with Newtonian, Schwarzschild, and extreme Kerr disk models. System parameters have been determined from optical observations (Green, Bailyn and Orosz 2003), such that distance is 3.2 kpc, inclination angle is  $70^\circ$ , and  $M = 7 M_\odot$ . We fixed the distance, while several different inclination angles are tried from  $0^\circ$  to  $80^\circ$ . The energy spectrum has a power-law hard-tail but contribution of which is minor below 10 keV and hardly affects discussion of the accretion disk spectrum. The power-law slope is fixed at 2.5 which matches the simultaneous high energy observation with BATSE (Zhang et al. 1997), and its normalization is allowed to be free within the range acceptable by BATSE. Hence, the free parameters are  $M$ ,  $\dot{M}$ , power-law normalization, and the hydrogen column density. Besides minor local features (see Gierliński, Maciołek-Niedźwiecki and Ebisawa 2001), all the models with different inclination angles can reasonably fit the observed accretion disk spectrum.

The Schwarzschild disk model at the correct inclination angle ( $i = 70^\circ$ ) gives a too small mass ( $1.8 M_\odot$ ) which is unacceptable (red curve in Fig.2 left). If we fix the mass at the correct value ( $7 M_\odot$ ), the disk spectrum cannot be hard enough to explain the observed spectrum (the “best-fit” is shown with green curve in Fig.2 left): The “too-hot” disk problem is thus evident.

It is of interest to see how the black hole mass depends on the inclination angle. Observation can constrain the projected disk area, which is proportional to square of the mass. Hence  $M \propto 1/\sqrt{\cos i}$  in the Newtonian case, and the black hole mass at  $i = 80^\circ$  is 2.4 times higher than that for the face-on disk. On the other hand, the mass increasing factor is 2.9 in the Schwarzschild case, and as much as  $\sim 10$  in the extreme Kerr case. This is because inclined relativistic disk spectra become harder, which is most conspicuous in the extreme Kerr disk (Fig.1). Given the observed spectra, to compensate the spectral hardening with inclination, the mass becomes necessarily larger.

The extreme ( $a = 0.998$ ) Kerr disk model with the correct inclination angle gives  $M = 15.9 M_\odot$ . Compared to the fit with Schwarzschild disk model ( $1.8 M_\odot$ ), significant increase of the mass does indicate the spectral hardening of the Kerr disk model. In fact, the derived mass is too large to be consistent with the realistic mass  $7 M_\odot$ , which probably suggests that  $a = 0.998$



**Fig. 2** ASCA GIS energy spectra of GRO J1655–40 (left panel) and IC 342 Source 1 (right). The best-fit Schwarzschild disk models are indicated in red, in which case the best-fit masses are too small ( $1.8 M_{\odot}$  and  $8.9 M_{\odot}$  for GRO J1655–40 and IC 342 respectively) compared to the mass determined from optical observations ( $7 M_{\odot}$  for GRO J1655–40), or that expected from the observed luminosity ( $100 M_{\odot}$  for IC 342). Schwarzschild disk spectra with the expected masses give too low temperatures to explain the observed accretion disk spectra for both cases (shown in green). Additional power-law component (blue in left panel) is required to fit the GRO J1655–40 spectrum.

is too high. In fact, Gierliński, Maciołek-Niedźwiecki and Ebisawa (2001) applied the Kerr disk model to the same ASCA energy spectrum of GRO J1655–40, and concluded that  $a$  is likely to be between 0.68 and 0.88 to be consistent with  $M = 7 M_{\odot}$ . To summarize, in agreement with Gierliński, Maciołek-Niedźwiecki and Ebisawa (2001), a standard Kerr disk model may explain the observed accretion disk spectra of GRO J1655–40 at the inclination angle  $i = 70^{\circ}$ . The Kerr metric is required, but not with the maximum angular momentum.

That GRO J1655–40 has probably a spinning black hole is also suggested by the recent discovery of 450 Hz QPO (Strohmayer 2001), as this frequency is higher than the Kepler frequency at the innermost stable orbit of a  $7 M_{\odot}$  Schwarzschild black hole. Precise analysis of the QPO characteristics from GRO J1655–40 suggests that the black hole is in neither a Schwarzschild nor a maximal Kerr black hole (Abramowicz and Kluźniak 2001), which is consistent with our energy spectral analysis.

## 2.2 Application to IC 342 Source 1

We assume the distance to the source 4 Mpc (Okada et al. 1998 and references there in). If isotropic emission is assumed, the luminosity will be  $1.7 \times 10^{40} \text{ ergs}^{-1}$  (1–10 keV) at this distance, thus  $M \geq 100 M_{\odot}$  is expected so as not to exceed the Eddington luminosity. All the fits with Newtonian, Schwarzschild, and Kerr disk models for different inclination angles. are acceptable, thus models may not be discriminated based on the quality of the fits. Note that the disk luminosities always exceed the Eddington limit more than 10 times in the Schwarzschild case.

The right panel in Fig.2 indicates the ASCA GIS spectrum and the best-fit Schwarzschild disk model (in red). For comparison, we show a Schwarzschild disk spectrum with  $M = 100 M_{\odot}$  at the Eddington limit (in green); we can clearly see that such an accretion disk has a too low temperature to explain the observed hard spectrum.

The face-on Kerr disk model gives  $M = 27.3 M_{\odot}$  and  $\dot{M} = 2.0 \times 10^{20} \text{ g s}^{-1}$  ( $\dot{M} = 16 \dot{M}_C$ ). A factor of  $\sim 3$  increase of the mass compared to the Schwarzschild case is due to slight hardening of the face-on Kerr disk spectrum. Note that *the super-Eddington problem does not disappear*, as the face-on Kerr disk spectrum is not very different from the Schwarzschild one (Fig.1). If we assume a very inclined disk with  $i = 80^\circ$ , we obtain  $M = 332 M_{\odot}$  and  $\dot{M} = 1.5 \times 10^{20} \text{ g s}^{-1}$  ( $\dot{M} = 1.0 \dot{M}_C$ ). Now the super-Eddington problem is solved, that is a consequence of the fact that the inclined Kerr disk spectrum is much harder than the Schwarzschild one. However, there will be two serious problems to accept the inclined Kerr disk model for ULXs in general: First, we do not know a mechanism to create  $\sim 350 M_{\odot}$  black holes. Second, it is very unlikely that most of the accretion disks in ULXs are largely inclined when seen from the earth.

### 3 THE SLIM DISK MODEL

#### 3.1 Characteristics of the slim disk model

So far, we have considered the standard optically thick accretion disk (Shakura and Sunyaev 1973) in which radial energy advection is neglected and all the gravitational energy release is converted to thermal radiation. In accretion disk theory (for a review, e.g., Kato, Fukue and Mineshige 1998), there is another stable optically thick solution, which is called ‘‘optically thick ADAF (advection-dominated accretion flow)’’ disk or, ‘‘slim’’ disk (Abramowicz et al. 1988), which takes place when mass accretion rate is around the super-Eddington rate or higher. In the slim disk, all the gravitational energy release is not converted to the thermal radiation, but significant part of the energy is carried inward due to radial advection. Slim disk is geometrically thick, and can be much hotter than the standard disk (Kato, Fukue and Mineshige 1998; Watarai et al. 2000).

One of the most significant observational characteristics of the slim disk is that the disk luminosity can exceed the Eddington limit by up to  $\sim 10$  times (Abramowicz et al. 1988; Szuszkiewicz, Malkan and Abramowicz 1996; Kato, Fukue and Mineshige 1998). This may be qualitatively understood as follows: At any disk radius, local radiation pressure may not exceed the vertical gravitational force, such that

$$F(r) \leq \frac{cGM}{\kappa r^2} \frac{h}{r}, \quad (1)$$

where  $F(r)$  is the energy flux,  $r$  the disk radius and  $h$  the half-thickness. Therefore,

$$\begin{aligned} L_{\text{disk}} &\equiv 2 \int_{r_{\text{in}}}^{r_{\text{out}}} 2\pi r F(r) dr \\ &\leq \frac{4\pi cGM}{\kappa} \int_{r_{\text{in}}}^{r_{\text{out}}} \frac{h}{r^2} dr \\ &\approx L_{\text{Edd}} \left( \frac{h}{r} \right) \ln \left( \frac{r_{\text{out}}}{r_{\text{in}}} \right), \end{aligned} \quad (2)$$

where  $r_{\text{in}}$  and  $r_{\text{out}}$  are inner and outer disk radius, respectively, such that  $\ln(r_{\text{out}}/r_{\text{in}}) \approx 10$ . In the standard disk, which is geometrically thin,  $h/r \leq 0.1$ , thereby  $L_{\text{disk}} \leq L_{\text{Edd}}$ . On the other hand, with the slim disk in which  $h/r \approx 1$ ,  $L_{\text{disk}} \leq 10 L_{\text{Edd}}$ .

In addition to that super-Eddington luminosities are permissible, slim disk has following observational characteristics (e.g., Kato, Fukue and Mineshige 1998; Watarai et al. 2000; Watarai, Mizuno and Mineshige 2001): (1) As the mass accretion rate exceeds the critical rate  $\dot{M}_C$ , energy conversion efficiency decreases due to advection. Hence the disk luminosity is no longer proportional to the mass accretion rate, but saturates at  $\sim 10L_{\text{Edd}}$ . (2) Innermost disk radius can be closer to the black hole than the last stable orbit, as mass accretion rate increases. Even in the Schwarzschild metric, innermost disk region inside  $6r_g$  can emit significant amount of X-rays. Thus slim disk can be “hotter” than the standard disk. (3) If radial dependence of the disk effective temperature is written as  $T_{\text{eff}} \propto r^{-p}$  (“ $p$ -free disk” below), the exponent  $p$  reduces from 0.75 (which is expected for the standard disk) to 0.5 as advection progressively dominates. Thus spectral difference from the standard disk will be noticeable.

### 3.2 Application to IC 342 Source 1

The slim disk model seems to be more likely to explain the spectral characteristics of ULXs. Mizuno, Kubota and Makishima (2001) studied spectral variations of several ULXs, and commonly found anti-correlation between the MCD parameters  $R_{\text{in}}$  and  $T_{\text{in}}$ , which is another observational feature of the slim disk (Watarai et al. 2000). Watarai, Mizuno and Mineshige (2001) calculated X-ray energy spectra of slim disks, and suggested that ULXs are slim disks around 10 – 30  $M_{\odot}$  black holes shining more luminously than Eddington limits. A characteristic spectral transition has been observed in IC 342 Source 1, such that the bright state in 1993 was represented with the MCD model spectrum, while in 2000 the source was dimmer and the energy spectrum was power-law like (Kubota et al. 2001). This spectral transition may be interpreted as the disk state transition between the blight slim disk state and another anomalous state (Kubota, Done and Makishima 2002).

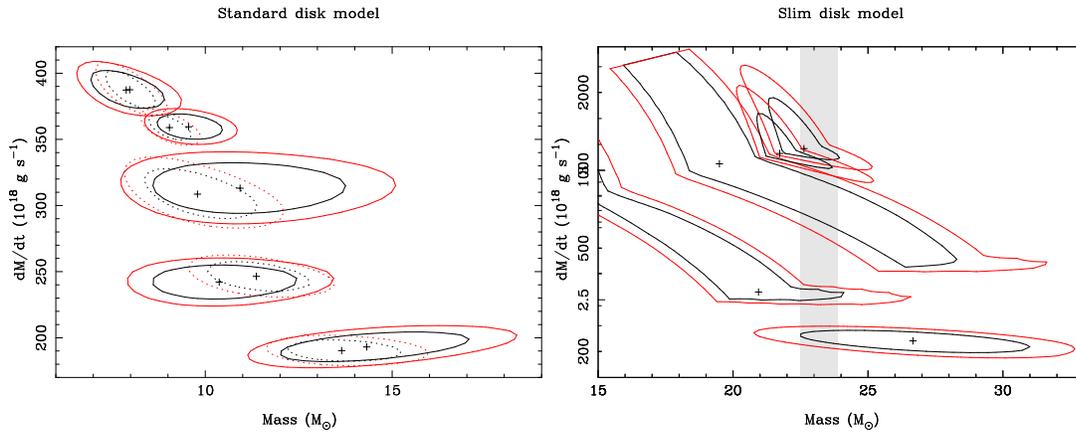
In the present paper, we fit the observed energy spectra of IC 342 Source 1 in 1993 with the same slim disk model calculated by Watarai, Mizuno and Mineshige (2001). Namely,  $\alpha = 0.01$ , and the local emission is a diluted blackbody with  $T_{\text{col}}/T_{\text{eff}} = 1.7$ . The model assumes the face-on geometry, and the distance is 4 Mpc. The energy spectra are calculated for each grid point of  $M = 10, 32, 100 M_{\odot}$  and  $\dot{M}/(L_{\text{Edd}}/c^2) = 1, 3, 10, 32, 100, 320, 1000$ . We fitted the observed spectra using XSPEC spectral fitting package with this grid-model, so that XSPEC interpolates the model spectra for other  $M$  and  $\dot{M}$  values.

We find the best fit parameters  $M = 19.8 M_{\odot}$  and  $\dot{M}/\dot{M}_C \approx 20$ . This mass accretion rate would give 20 times the Eddington luminosity in the case of the standard disk. However, since slim disk is less efficient at  $\dot{M} \geq \dot{M}_C$ , the disk luminosity is in fact only  $\sim 6$  times the Eddington luminosity, which is allowed in the slim disk.

The slim disk model can fit the observed spectra reasonably well ( $\chi^2/\text{dof} = 1.40$ ), but not as good as the standard disk models ( $\chi^2/\text{dof} \approx 0.90$ ). Also, the hydrogen column density is significantly larger with the slim disk model ( $\sim 9 \times 10^{21} \text{ cm}^{-2}$ ) compared to those with the standard disk models ( $3 - 5 \times 10^{21} \text{ cm}^{-2}$ ). This is because the spectral difference between the best-fit slim disk model and standard disk spectra is largest in the lower energy band. More realistic slim disk spectral model is expected to fit the observed spectra better.

### 3.3 Spectral Variation of IC 342 Source 1

The characteristic anti-correlation between  $R_{\text{in}}$  and  $T_{\text{in}}$  discovered by Mizuno, Kubota and Makishima (2001) is considered to be a characteristic of the slim disk. Watarai, Mizuno and Mineshige (2001), through indirect comparison of the MCD parameters and slim disk spectra, claimed that this spectral variation may be explained with a slim disk at a constant  $M$  only



**Fig. 3** Spectral variation of IC 342 Source 1 observe in September 1993. The same datasets as in Mizuno, Kubota and Makishima (2001) are used. The left indicates the variation of mass and mass accretion rates obtained by applying the standard Schwarzschild disk model (GRAD model). Contours with dotted lines are from fitting in 0.5–10 keV, and those with solid lines are from 2–10 keV. The two contour levels indicate 68% ( $1\sigma$ ) and 90% error regions for two parameters. The right panel is obtained through application of the slim disk model in 2–10 keV. The region marked with gray indicates that the observed spectral variation is achieved with constant  $M$  and variable mass accretion rates.

by varying the mass accretion rate. We demonstrate this claim by directly fitting the ASCA IC 342 Source 1 spectra with the slim disk model.

We use the same spectral datasets used by Mizuno, Kubota and Makishima (2001). The observation period is split into five periods depending on the flux levels. For each period, GIS and SIS spectra are fitted simultaneously to achieve the better statistics. In the top panel of Fig.3, we show  $M$  and  $\dot{M}$  variation obtained with the face-on GRAD model. We fixed the hydrogen column density at the average value ( $N_{\text{H}} = 5.2 \times 10^{21} \text{ cm}^{-2}$ ), so that the free parameters are only  $M$  and  $\dot{M}$ . The reduced  $\chi^2$  is less than unity for all the five spectra. We see clear anti-correlation between these two parameters, which is just rephrasing the  $R_{\text{in}} - T_{\text{in}}$  anti-correlation discovered by Mizuno, Kubota and Makishima (2001). Since  $M$  must not vary in the real world, this relation is telling that the standard accretion disk is not a proper model for IC 342 Source 1. The spectral variation is clearly seen using only the 2–10 keV band, though less clear than using the entire 0.5–10 keV band.

Since the present slim disk model does not fit the observed spectra well below  $\sim 1.5$  keV, we study spectral variation only using 2 – 10 keV (then reduced  $\chi^2$  will be  $\sim 1$ ). For fair comparison, the hydrogen column density was fixed to the same average value as used in the GRAD model fitting. The  $M$  and  $\dot{M}$  relation obtained from the slim disk fitting is shown in the bottom panel in Fig.3. We see that  $M$  in the range of  $22.5 M_{\odot}$  to  $23.9 M_{\odot}$  is consistent with all the five spectra. Therefore, based on the slim disk model, we may interpret the observed characteristic spectral variation of IC 342 Source 1 as a result of simple mass accretion rate variations.

#### 4 ORIGIN OF THE ULTRA-LUMINOUS X-RAY SOURCES

We have shown that the present slim disk model, though still primitive, is likely to explain the observed super-Eddington luminosities, hard energy spectra, and spectral variations of IC 342 Source 1, in agreement with Watarai, Mizuno and Mineshige (2001). Whereas Watarai, Mizuno

and Mineshige (2001) indirectly compared the observed spectra and the slim disk model spectra, we directly fitted the observed spectra with the slim disk model, and made a quantitative comparison. Thereby, we obtained the black hole mass  $\sim 20 M_{\odot}$ , and the disk luminosity  $\sim 6$  times the Eddington luminosity for IC 342 Source 1. Thus, “intermediate mass black holes” are not required to explain the observed luminosity  $\sim 10^{40} \text{ erg s}^{-1}$ .

In our Galaxy, the most massive stellar black hole is  $\sim 14 M_{\odot}$  in GRS 1915+40 (Greiner, Cuby and McCaughrean 2001), as far as currently measured. However, more massive stellar black holes may well exist in other galaxies. In fact, stellar evolution theory says main-sequence stars can have a maximum mass  $\sim 60 M_{\odot}$  (Schwarzschild and Härm 1959), and the final black hole mass could be theoretically as large as its progenitor beyond  $40 M_{\odot}$  (Fryer 1999). Observationally, Grimm, Gilfanov and Sunyaev (2003) found that there exists such a universal luminosity function of X-ray binaries that is applicable to several different galaxies including Milky way, where normalization for different galaxies are proportional to the star-forming rates. Galaxies which are active in star formation tend to have more luminous and massive compact objects, and the maximum cut-off luminosity is  $\sim 10^{40} \text{ erg s}^{-1}$ . We suggest that ULXs with luminosities of  $\sim 10^{40} \text{ erg s}^{-1}$  are black holes having a few tens of solar mass, which reside at the brightest end of the X-ray binary luminosity function. Observed evidence of the association between some ULXs and star forming region may support our idea (e.g., Matsushita et al. 2000).

## 5 CONCLUSION

1. In order to solve the “too-hot disk” problem of ULXs and Galactic superluminal jet sources, we have carefully studied energy spectra of the standard accretion disk and slim disk. In particular, we have calculated the extreme Kerr disk spectral model, and studied how relativistic effects and disk inclination angle affect the observed disk spectra.
2. We have found that the standard Kerr disk model can successfully explain the observe hard spectra of GRO J1655–40, because the Kerr disk spectra become significantly harder than Schwarzschild ones when the disk is significantly inclined, which is exactly the case for GRO J1655–40. Another super-luminal jet source GRS 1915+105 is also a highly inclined system (Greiner, Cuby and McCaughrean 2001), so that the idea of inclined Kerr disk model may be plausible too.
3. The Kerr disk spectra are not significantly harder than the Schwarzschild disk when disk inclination angle is not large. We conclude that the standard Kerr disk model is not appropriate to explain the observed hard spectra of most ULXs, since (1) it is unlikely that accretion disks in most ULXs are preferentially inclined, and (2) if the inclined Kerr disk is applied, unreasonably large black hole mass ( $\sim 300 M_{\odot}$ ) is required.
4. We have calculated the slim disk spectra, and applied to the observed spectra of IC 342 Source 1 in 1993, when the source is in the high state. Although the current primitive slim disk model does not perfectly fit the data, we found the slim disk can explain the observed super-Eddington luminosity, hard X-ray spectra, and spectral variation successfully. In particular, the observed characteristic spectral variation is explained with a constant mass at  $M \sim 20 M_{\odot}$ , only varying the mass accretion rate.
5. We propose ULXs are binary systems with a few tens of solar mass black holes, which reside at the bright end of the X-ray binary luminosity function. Such moderately massive stellar black holes may not exist in our Galaxy, but presumably not uncommon in the galaxies where massive star formation is much more active.

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