ACCRETION DISK SPECTRA OF THE ULTRA-LUMINOUS COMPACT X-RAY SOURCES IN NEARBY SPIRAL GALAXIES AND THE SUPER-LUMINAL JET SOURCES

Ken Ebisawa, Aya Kubota, Tsunefumi Mizuno, and Piotr Życki

ABSTRACT

The Ultra-luminous Compact X-ray Sources (ULXs) in nearby spiral galaxies and the Galactic super-luminal jet sources share the common spectral characteristic that they have extremely high disk temperatures which cannot be explained in the framework of the standard accretion disk model in the Schwarzschild metric. We examine several possibilities to solve this “too-hot” disk problem. In particular, we have calculated an extreme Kerr disk model to fit the observed spectra. We found that the Kerr disk will become significantly harder compared to the Schwarzschild disk only when the disk is highly inclined. For super-luminal jet sources, which are known to be inclined systems, the Kerr disk model may work if we choose proper values for the black hole angular momentum. For the ULXs, however, the Kerr disk interpretation will be problematic, as it is highly unlikely that their accretion disks are preferentially inclined.

Key words: super-luminal jet sources; ultra-luminous X-ray sources; accretion disks; black holes.

1. ULTRA-LUMINOUS COMPACT X-RAY SOURCES (ULXS)

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). These luminosities are too small for AGNs, and most ULXs are actually located significantly far from the optical photometric center of the galaxies.

Significant time variations have been detected from ULXs, and their energy spectra are fitted well with optically thick accretion disk models (Okada et al. 1998; Mizuno et al. 1999; Makishima et al. 2000). These observational facts suggest that the ULXs are moderately massive black holes, which may be scale-up versions of the Galactic black holes in the “high” state (=soft-state), in which the soft thermal spectrum is established to be emission from optically thick accretion disks. So that the observed luminosity (assuming isotropic emission) does not exceed the Eddington limit $L_E = 1.5 \times 10^{38} (M/M_\odot)$ erg s$^{-1}$, the black hole mass will have to be up to $\sim 100 M_\odot$.

In addition to that the energy spectra are fitted with optically thick accretion disk models, recently found bimodal spectral transitions from two ULXs IC342 (Kubota et al. 2000) will further demonstrate their resemblance with the Galactic black hole candidates.

2. THE “TOO HOT” ACCRETION DISK PROBLEM

GRS 1915+105 and GRO J1655–40 are the two well-studied Galactic super-luminal jet sources, and the latter is an established black hole binary with mass measurement of the central source ($M \approx 7M_\odot$; Orosz and Bailyn 1997). Although these X-ray energy spectra are basically fitted with an optically thick accretion disk plus power-law, which is a canonical model for the high-state black hole candidates, it has been noticed that the characteristic disk color temperature of the jet sources can be as high as $\sim 1.3 – 2.0$ keV (e.g., Belloni et al. 1997; Zhang et al. 1997a; Tomsick et al. 1999); this is systematically higher than other non-jet, well-studied black hole candidates such as Cyg X-1 and LMC X-3, whose disk temperatures are almost always less than $\sim 1$ keV.

Interestingly, the unusually high disk color temperature, $\sim 1.5 – 1.8$ keV, is also observed from the ULXs in IC342 (Okada et al. 1998), NGC4565 (Mizuno et al. 1999) and other galaxies; in fact this seems to be a common spectral characteristic of the ULXs (Makishima et al. 2000).

Below, we briefly explain how the characteristic disk
where we define the Eddington mass accretion rate as
\[ \dot{M}_{\text{Edd}} = 3 \times 10^{18} \frac{M}{M_\odot} \text{ g s}^{-1}, \]
so that \( \dot{M}/\dot{M}_{\text{Edd}} = 1 \) gives the Eddington luminosity. From this formula, we can see that an optically thick accretion disk around a 7 \( M_\odot \) Schwarzschild black hole may not be hotter than the color temperature \( \sim 1.3 \) keV. Note that as the mass increases the maximum disk temperature decreases with \( \dot{M}^{-1/4} \), which is the reason that the AGN blue bumps appear in the UV band.

We show examples of the observed “too-hot” accretion disks in GRO J1655–40 and an ULX in IC342 (Figure 1). On the left panel of Figure 1, we show an ASCA GIS spectrum of GRO J1655–40 in 1995 August, when the source is in one of the brightest states. The energy spectrum may be fitted with an optically thick accretion disk model plus a power-law tail which extends up to the BATSE energy band with a photon-index of \( \sim 2.5 \) (Zhang et al. 1997a). Contribution of the hard-tail in the ASCA band below 10 keV (the yellow line in the panel) is rather minor and will not affect the discussion of the optically thick accretion disk model. We applied a Schwarzschild disk model by Hanawa (1989) with the distance and inclination angle being fixed at 3.2 kpc and 70\( ^\circ \) respectively (Orosz and Bailyn 1997), and \( T_{\text{col}}/T_{\text{eff}} = 1.7 \). We show the best-fit model which was obtained by assuming the most likely distance of 4 Mpc (Okada et al. 1998 and references therein) and isotropic emission, thus \( M > 80 M_\odot \).
is expected so that the luminosity does not exceed the Eddington limit. We fit the observed spectrum with the Schwarzschild disk model by Hanawa (1989), allowing the mass and mass accretion rate to be free parameters, assuming the face-on geometry. The best-fit model gives $M = 12.6M_\odot$ and $\dot{M} = 3 \times 10^{20}$ g s$^{-1}$ ($\dot{M}/\dot{M}_{Edd} = 7.9$). Obviously, such a super-Eddington luminosity is very unlikely. Even if we assume a possible minimum distance of 1.5 Mpc (Okada et al. 1998), $\dot{M}/\dot{M}_{Edd} \approx 3$ and the super-Eddington problem is not solved. Note that changing the inclination angle does not help, as both $M$ and $\dot{M}_{Edd}$ are proportional to $\cos i$ and their ratio is invariant. For a comparison, we have shown a Schwarzschild disk model spectrum with $M = 100M_\odot$ at the Eddington limit; it is obvious that the observed spectrum is much harder than the model spectrum.

3. SEVERAL POSSIBILITIES TO EXPLAIN THE TOO-HOT DISKS

3.1. Large $T_{col}/T_{eff}$?

A naive solution to explain the apparently hard disk spectrum may be to allow $T_{col}/T_{eff}$ to be much greater than 1.7, in which case the effective temperature of the disk remains the same, but significant Comptonization in the upper-layer hardens the disk spectra. This is an idea by Borozdin et al. (1998) who adopted $T_{col}/T_{eff} = 2.7$ for GRO J1655–40 a posteriori so that the mass derived from the X-ray model fitting agrees with the dynamical mass, as $2.8M_\odot \times (2.7/1.7)^2 \sim 7M_\odot$.[1]

However, it is unlikely that $T_{col}/T_{eff} \gg 1.7$ holds universally. First, the spectral hardening factor can be calculated by solving the vertical radiative transfer in the disk, and several independent calculations (e.g., Shimura and Takahara 1995; Ross and Fabian 1996) indicate that $T_{col}/T_{eff}$ is in the range of 1.5 – 1.9 for reasonable values of the $\alpha$ parameter. Second, assuming $T_{col}/T_{eff} \approx 1.7$, the black hole mass estimated from the X-ray spectral fitting agrees fairly well with the dynamical mass derived from optical observations for most high-state black hole candidates such as LMC X-3 (Ebisawa et al. 1993) and Cyg X-1 (Dotani et al. 1997). If we apply $T_{col}/T_{eff} = 2.7$ for other well-known black hole candidates, we will end up with unusually high black hole masses (Shrader and Titarchuk 1999). Also, application to the accretion disks in neutron star binaries will give too large masses which are not allowed for neutron stars.

3.2. Non-standard Disk Structure?

Instead of the standard optically thick disk in which all the released gravitational energy is thermalized and goes into the radiation, if energy transfer due to advection is introduced, we will have a different accretion disk structure and spectrum. Watarai et al. (2000, 2001) considered the optically thick Advection Dominated Accretion Flow (ADAF) model (slim-disk) which may be valid near the Eddington limit. They pointed out that this model may explain the hard disk spectrum of the super-luminal jet sources as well as apparently small inner disk radii.

According to Watarai et al. (2000, 2001), $T(r) \propto r^{-0.5}$ holds in the optically thick ADAF model, as opposed to $T(r) \propto r^{-0.75}$ which is the case for the standard disk. To examine this hypothesis, we have calculated an accretion disk model with $T(r) \propto r^{-0.5}$ and applied to the ASCA spectrum of GRO J1655-40. As a result, we obtained a very poor fit with a reduced $\chi^2$ of $\sim 40$. This is unfavorable to the optically thick ADAF model, though more precise spectral calculation and detailed comparison with the observation will be of interest.

3.3. Kerr Metric?

In the Schwarzschild metric, the last stable orbit around the black hole is $6r_g$, while in the Kerr metric it can go down to $r_{in} = 1.24 r_g$ for the prograde case with an extreme angular momentum of $a = 0.998$. If the inner edge of the accretion disk approaches the black hole accordingly, the local disk temperature can get higher, hence may explain the too-hot accretion disk spectra (Zhang et al. 1997b; Makishima et al. 2000). To examine this hypothesis, we have to calculate the Kerr disk model taken into account full relativistic effects.

Precise Kerr disk model calculations have been carried out by several authors including Asaoka (1989), Laor et al. (1990) and Gielinski et al. (1999, 2000). In this paper, we calculate the Kerr disk spectrum using the transfer function computed by Laor et al. (1990) for $a = 0.998$ (when the conversion efficiency becomes 0.366 and $\dot{M}_{Edd} = 4.6 \times 10^{17}(M/M_\odot)$ g s$^{-1}$). To make the relativistic effects more apparent, we assume a constant $T_{col}/T_{eff}$ and do not take into account the inclination dependent limb-darkening, which Laor et al. (1990) and Gielinski et al. (1999, 2000) considered.

The calculated energy spectra are shown in Figure 2 for several inclination angles. We see that the energy spectra are strongly dependent on the inclination angle in higher energy bands. At lower energies, where most of the emission is from the outer parts of the disk, the flux decreases with $\cos i$. On the other hand, the hard emission from innermost parts of the disk ($1.26 r_g < r < 7 r_g$) is enhanced as the disk is more inclined, due to strong light bending and
The Eddington luminosity is assumed, and the contributions from inner, middle, and outer parts get dominant in the highest band, as a result the total disk spectrum becomes much harder than the Schwarzschild one. As the disk approaches to edge-on, however, contribution from the innermost part gets dominant in the highest band, as a result the total disk spectrum becomes much harder than the Schwarzschild disk.

We have applied the Kerr disk model to GRO J1655–40 and the Source 1 in IC342. For GRO J1655–40, the inclination angle is fixed to $i = 70^\circ$ and $T_{col}/T_{eff} = 1.7$ is assumed. If we allow the mass and mass accretion rate to be free, we obtain $M = 16.4M_\odot$ and $\dot{M} = 3.5 \times 10^{17} \text{ g s}^{-1}$ ($M/M_{\text{Edd}} = 0.046$). Compared to the fit with Schwarzschild disk model ($M = 2.8M_\odot$), significant increase of the mass does indicate the spectral hardening of the Kerr disk model with a large inclination angle. In fact, the derived mass is too large, and further tuning of the angular momentum $a$ will be required to achieve the realistic mass ($7M_\odot$). Gieliński et al. (1999, 2000) calculated the Kerr disk model for several different $a$ values, and found that $a = 0.75$ gives $6.4M_\odot$ for GRO J1655–40.

The IC 342 fit with the face-on Kerr disk model gives (assuming $d = 4 \text{ Mpc}$) $M = 27.6M_\odot$ and $\dot{M} = 2.2 \times 10^{20} \text{ g s}^{-1}$ ($L = 17L_{\text{Edd}}$). Only a factor of $\sim 2$ increase of the mass is due to slight hardening of the face-on Kerr disk model compared to the Schwarzschild one. Note that the super-Eddington problem is not solved. If we assume $i = 80^\circ$, we obtain $M = 340M_\odot$ and $\dot{M} = 1.7 \times 10^{20} \text{ g s}^{-1}$ ($L = 1.1L_{\text{Edd}}$). Then the super-Eddington problem will be almost solved, but such a large mass seems to be unlikely. Also, it is very unlikely that most of the accretion disks in ULXs are inclined when seen from the earth. Therefore, a Kerr disk interpretation of the ULXs will be problematic, unless considering some other mechanisms to make the disk spectra apparently harder.

REFERENCES

Asaoka, I. 1989, PASJ, 41, 763
Belloni, T. et al. 1997, ApJ, 488, L109
Borozdin, K. et al. 1999, ApJ, 517, 367
Colbert, E.J.M. & Mushotzky, R.F. 1999, ApJ, 519, 89
Dotani, T. et al. 1997, ApJ, 485, L87
Ebisawa, K. et al. 1993, ApJ, 403, 683
Fabbiano, G. 1988, ARA&A, 27, 87
Gieliński, M. et al. 1999, AN, 320, 350
Gieliński, M. et al. 2000, submitted to MNRAS
Hanawa, T. 1989, ApJ, 341, 948
Kubota, A. et al. 2000, ApJL, 547, 119
Laor, A. et al. 1990, MNRAS, 242, L560
Makishima K. et al. 2000, ApJ 535, 632
Mizuno, T. et al. 1999, PASJ, 51, 663
Okada, K. et al. 1998, PASJ, 50, 25
Orosz, J. A. and Bailyn, C. D. 1997, ApJ, 477, 876
Ross, R.R. & Fabian, A. C. 1996, MNRAS, 281, 637
Shimura, T. and Takahara, F. 1985, ApJ, 445, 780
Shrader, C. and Titarchuk, L. 1999, ApJ, 512, 892
Tomsick J. et al. 1999, ApJ, 512, L121
Watarai, K. et al. 2000, PASJ, 52, 133
Watarai, K. et al. 2001, ApJL, 549, 77
Zhang, S. N. et al. 1997a, ApJ, 479, 381
Zhang, S. N. et al. 1997b, ApJ, 482, L155

Figure 2. The Kerr accretion disk model with an extreme angular momentum ($a = 0.998$) for the inclination angles $\mu \equiv \cos i = 0.1, 0.3, 0.5, 0.7$ and 0.9. The distance and mass are assumed to be 1 kpc and 1 $M_\odot$ respectively. The Eddington luminosity is assumed, and $T_{col}/T_{eff} = 1$. Solid lines indicate the total disk spectra, and contributions from inner ($1.26r_g < r < 7r_g$), middle ($7r_g < r < 400r_g$), and outer parts ($400r_g < r$) are also plotted separately either by dotted or broken lines.