第14回　降着円盤からのX線放射

2021年7月5日　20:21

The standard accretion disk model (α-disk model)

Shakura and Sunyaev A&A 24, 337 (1973)

Black Holes in Binary Systems. Observational Appearance

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Standard disk
標準降着円盤
α-disk モデル

Summary. The outward transfer of the angular momentum of the accreting matter leads to the formation of a disk around the black hole. The structure and radiation spectrum of the disk depend, mainly on the rate of matter inflow $\dot{M}$ into the disk at its external boundary.

質量降着率

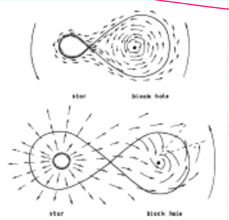


Fig. 1. Two regimes of matter capture by a collapsar: a) a normal companion fills up its Roche lobe, and the outflow goes, in the main, through the inner lagrangian point; b) the companion's size is much less than Roche lobe the outflow is connected with a stellar wind. The matter loses part of its kinetic energy in the shock wave and thereafter, gravitational capture of accreting matter becomes possible

α-disk model　粘性テンソル が 圧力に比例すると仮定した　比例係数がα

If the viscosity in the disk ($r\phi$-component of the shear stress tensor, $t_{r\phi}$) is assumed to be proportional to the pressure, P, as

$t_{r\phi} = -\alpha P$

the accretion disk equations are *solved* , where α is called **the viscous parameter** ($0 < \alpha < 1$).

αパラメター

Radial dependence of the disk temperature and the disk spectra are calculated as a function of mass accretion rate and α.

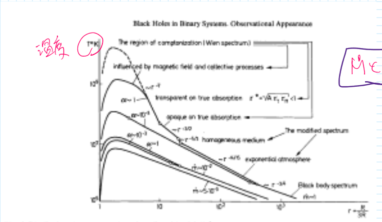


Fig. 12. Distribution of temperature along the radius of the disk if $\dot{M}$ and the parameter α are different

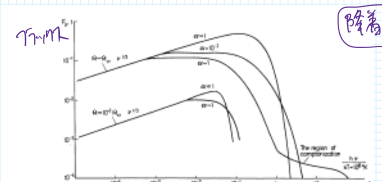


Fig. 3. The integral radiation spectrum of the disk, computed for different $\dot{M}$ and α

Basic characteristics of the standard disk (Shakura and Sunyaev disk; α-disk model)

1. In the gas-pressue dominated disk, derive the relationship among the disk thickness, temperature, and gravitational potentail

$P \approx \frac{\rho k T}{m}$　理想気体

$\frac{dP}{dh} \approx -\frac{GM\rho}{r^2}\frac{h}{r}$　圧力平衡　$\Rightarrow$　$\frac{P}{h} \approx \frac{GM\rho}{r^2}\cdot\frac{h}{r}$

$\frac{P}{\rho} \approx \frac{GM}{r}\left(\frac{h}{r}\right)^2$

$\frac{P}{h} \approx \frac{1}{h}\cdot\frac{\rho k T}{m} \approx \frac{GM\rho}{r^2}\cdot\frac{h}{r}$

$\frac{\cancel{\rho} k T}{m \cancel{h}} \approx \frac{GM\cancel{\rho}}{r^2}\frac{h^2}{r^2}$

$\frac{kT}{m} \approx \frac{GM}{r}\left(\frac{h}{r}\right)^2$

~1 keV　diskの温度

$\frac{kT}{\left(\frac{GMm}{r}\right)} \approx \left(\frac{h}{r}\right)^2$

potential energy ~GeV　　diskの厚み

$\frac{GMm}{r_s} \approx \frac{\cancel{GM}m}{\frac{2\cancel{GM}}{c^2}} \approx \frac{1}{2}mc^2 \approx \frac{1}{2}$ GeV

2. In the standard disk model, derive the relationships among the viscous parameter (α), disk thickness(h) , radial velocity(v_r), rotational velocity(v_ϕ), and sound velocity(v_s)

$v_\varphi = \sqrt{\frac{GM}{r}}$　　$v_s \approx \sqrt{\frac{P}{\rho}}$　音速

$t_{r\varphi} \approx \alpha P \approx \alpha \rho v_s^2$

$\approx \rho v_{turb}^2 \approx \rho v_r v_\varphi$

乱流速度

$\alpha \approx \frac{v_r v_\varphi}{v_s^2} \leq 1$

$\frac{P}{\rho} \approx v_s^2 \approx \frac{GM}{r}\left(\frac{h}{r}\right)^2 \approx v_\varphi^2\left(\frac{h}{r}\right)^2$

$v_\varphi \approx v_s\left(\frac{h}{r}\right) \gg v_s$

$v_r \approx \frac{\alpha v_s^2}{v_\varphi} \approx \frac{\alpha v_s^2}{v_s\frac{r}{h}} \approx \alpha v_s\left(\frac{h}{r}\right) < v_s$

$\approx \alpha v_\varphi\left(\frac{h}{r}\right)^2 \ll v_\varphi$

Standard disk ⇒ geometrically thin

- 冷たいdisk → optically th… → geometrical…
- 熱いdisk → optically… → geometri…

α↗ v_r↗ 粘性が大きい → 落ちる速さが大きい
α↘ v_r↘ 小さい → 遅い

αパラメター

Situation about accretion disk in mid- 1980's.

From High Energy Astrophysics by Kats (1986)　ちょんから(1987年)の前

The theory of discs is in a much more primitive state than that of stars, because one essential constitutive relation is not understood, their rate ϵ of viscous heating. This resembles the problem of stellar structure prior to the development of nuclear physics in the 1930's. We may be worse off than this, because so few direct observations of discs are possible. What little data exist (for example, for discs around likely black holes like Cygnus X-1) indicates that real discs are not steady objects radiating from optically thick photospheres (as the theory assumes), but that they are wildly variable, release much ick (光学的に厚い)

ly thin (幾何学的に薄い)

y thin (光学的に薄い)

cally thick (幾何学的に厚い)

structure prior to the development of nuclear physics in the 1930's. We may be worse off than this, because so few direct observations of discs are possible. What little data exist (for example, for discs around likely black holes like Cygnus X-1) indicates that real discs are not steady objects radiating from optically thick photospheres (as the theory assumes), but that they are wildly variable, release much of their energy in optically thin regions, and may have important nonthermal processes. It may be appropriate to compare our present understanding of discs to Galileo's understanding of sunspots and solar activity.

$\simeq \alpha v_\varphi \left(\frac{h}{r}\right)^2 \ll v_\varphi$

$\alpha \uparrow$ $v_r \nearrow$ 粘性が大きい → 落ちる速さが大きい
$\alpha \downarrow$ $v_r \searrow$ 小さい → おそい

→ geometri

Japanese Ginga satellite launched in 1987.

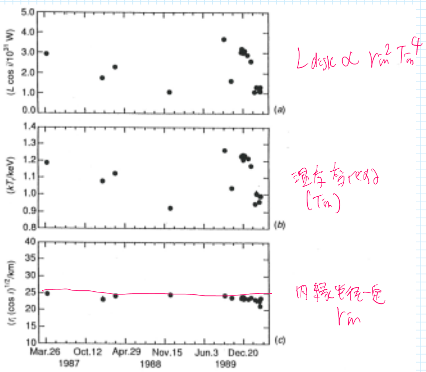
Carry out precise measuements of X-ray energy spectra from acrretion disk.

Longair "High energy astrophysics" 2nd edition (1994)

Now, both the luminosity, L, and the temperature, T_i, can be measured for the soft component and so the quantity $r_i \cos^{1/2} i$ can be found. Inoue (1992) analysed variations of temperature and luminosity for these sources over a three-year period and found that the inferred value of $r_i \cos^{1/2} i$ remained remarkably constant, despite large variations in the luminosity of the soft component (Fig. 16.22). He suggested that r_i corresponds to the last stable orbit about the black hole, for example, in the case of LMC X-3, the inner radius corresponding to $r_i \cos i = 25$ km. A more complete analysis, taking account of the effects of special and general relativity has suggested that the mass of the black hole in LMC X-3 is about $5M_\odot$.

ISCO
(Innermost Stable Circular Orbit)

This is a remarkable result, but it is clearly dependent upon a number of assumptions, particularly that the accretion disc is optically thick. As was argued in Section 16.3.6, the inner regions of thin accretion discs are often expected to be optically thin. Nonetheless, this analysis is indicative of the type of programme which, if correct, provides direct evidence about the process of accretion onto black holes in relatively nearby systems.



$L_{disk} \propto r_{in}^2 T_{in}^4 \propto T_{in}^4$

温度変化する
(T_{in})

内縁半径一定
r_{in}

Figure 16.22. Time histories of the best-fit parameters to the soft component of the X-ray spectrum of LMC X-3 obtained by the Japanese Ginga satellite. (*a*) The bolometric luminosity of the sources; (*b*) the inferred temperature at the inner radius of the accretion disc; (*c*) the inferred inner radius, r_i, of the accretion disc. i is the inclination angle of the plane of the orbit to the plane of the sky. (From H. Inoue (1992), *Proc. Texas/ESO-CERN Symposium on Relativistic astrophysics, cosmology and fundamental particles*, eds J.D. Barrow, L. Mestel and P.A. Thomas, pp. 86–103. New York: New York Academy of Sciences.)

Solutions and stability of accretion disk models

Abramowicz et al. (1995)

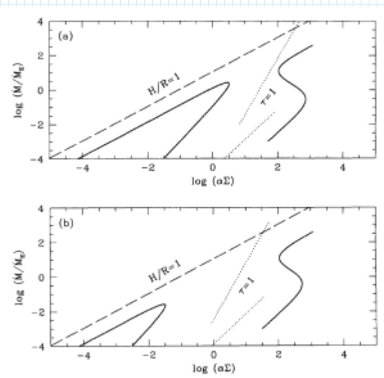
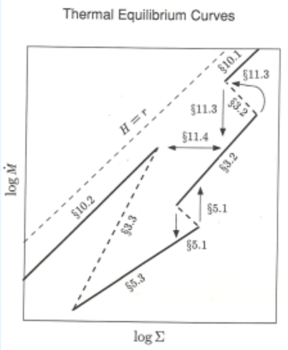


Fig. 3.—(*a*) Thermal equilibria for optically thick (the right solid S-shaped line) and optically thin (the left solid line) accretion disks. The upper branches represent advection-dominated solutions. Configurations above the dotted lines $\tau = 1$ are optically thin, where τ is the effective optical depth calculated by assuming that the pressure is dominated either by radiation (the upper one) or by gas (the lower one). The parameters assumed here are $M/M_\odot = 10$, $r = 5$, $\alpha = 0.1$, and $\xi = 1$. (*b*) The same as (*a*) except for $\alpha = 0.01$.

Kato, Fukue, and Mineshige (1998) Black-hole Accretion Disks cally thick(幾何学的に厚い)



Section 3.2 --- Optically thick disks → Standard Shakura & Sunyaev disk, high-soft state of black hole binaries
Section 3.3 --- Optically thin disk → unstable (not observed)
Section 5.1 --- Thermal-ionization Instability→ explains the UV-optical dwarf-novae ("disk instability model" by Osaki 1974)
Section 5.3 --- Emission line formation of during quiescence (optically thick disk around white-dwarfs) → double horn emission lines
Section 10.1 --- Radiation pressure dominated disk, optically thick advection dominated accreting flow (ADAF) → slim disk
Section 10.2 --- Optically-thin one-temperature disk, optically thin ADAF→ low-hard state of black hole binaries
Section 11.3 --- Relaxation oscillations in hot accretion disks → rapid and cyclic-variation of GRS1915+105
Section 11.4 --- Advection dominated flow in X-ray novae→ State transition between the high-soft state and low-hard state

Origin of the turbulent viscosity in the accretion disk
Balbus and Hawley (1991)

A POWERFUL LOCAL SHEAR INSTABILITY IN WEAKLY MAGNETIZED DISKS.
I. LINEAR ANALYSIS

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Received 1990 November 1; accepted 1991 January 16

ABSTRACT
In this paper and a companion work, we show that a broad class of astrophysical accretion disk is dynamically unstable to axisymmetric disturbances in the presence of a weak magnetic field. Because of the ubiquity of magnetic fields, this result bears upon gaseous differentially rotating systems quite generally. This work presents a linear analysis of the instability. (The companion work presents the results of nonlinear numerical simulations.) The instability is local and extremely powerful. The maximal growth rate is of order the angular rotation velocity and is independent of the strength of the magnetic field, provided only that the energy density in the field is less than the thermal energy density. Unstable axisymmetric disturbances require the presence of a poloidal field component, and are indifferent to the presence of a toroidal component. The instability also requires that the angular velocity be decreasing outward. In the absence of a powerful dissipation process, there are no other requirements for instability. Fluid motions associated with the instability directly generate both poloidal and toroidal field components. We discuss the physical interpretation of the instability in detail. Conditions under which saturation occurs are suggested. The nonemergence of the classical Rayleigh criterion for shear instability in the limit of vanishing field strength is noted and explained. The instability is sensitive neither to disk boundary conditions nor to the constitutive fluid properties. Its existence precludes the possibility of internal (noncompressive) wave propagation in a disk. If present in astrophysical disks, the instability, which has the character of an interchange, is very likely to lead to generic and efficient angular momentum transport, thereby resolving an outstanding theoretical puzzle.
Subject headings: accretion — hydrodynamics — hydromagnetics — instabilities

1. INTRODUCTION

A long-standing challenge to the theory of accretion disks has been to show from first principles a mechanism capable of generating a turbulent viscosity, since the angular momentum transport resulting from the action of ordinary molecular viscosity is extremely inefficient (Pringle 1981). In this work and a companion paper (Hawley & Balbus 1991, hereafter II), we show that accretion disks are subject to a very powerful shearing instability mediated by a weak magnetic field of any plausible astrophysical strength. We suggest that this instability is of some relevance to understanding the origin of turbulent viscosity in accretion disks.

→ αを仮定しなくても MHDの計算で diskが解ける!

Radiative transfer in the optically thick accretion disk
Local accretion spectrum is "diluted blackbody", where the color temperature, T_{col} is larger than the effective temperature T_{eff} due to Comptonization in the hot disk atmosphere.
If T_{col}/T_{eff} (color correction) is strongly dependent on the disk radius and/or disk luminosity, the emerging disk spectrum would be very complicated!

Shimura and Takahara (1995)

ON THE SPECTRAL HARDENING FACTOR OF THE X-RAY EMISSION FROM ACCRETION DISKS IN BLACK HOLE CANDIDATES

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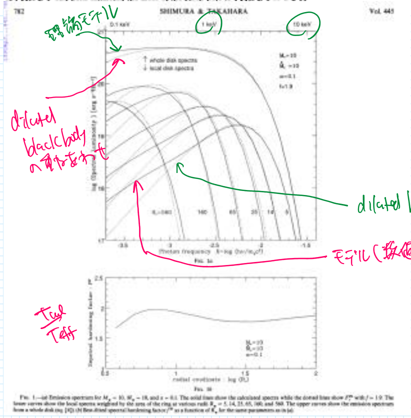
ABSTRACT
Radiation spectrum and the spectral hardening factor of an accretion disk around a Schwarzschild black hole with a mass of 1.4, 3, and 10 $M_\odot$ are determined by solving the vertical structure and radiative transfer self-consistently. When a viscous parameter $\alpha \sim 0.1$, for accretion rates close to the Eddington limit, the local spectrum can be described by the diluted blackbody spectrum with the spectral hardening factor $f \sim 1.8$–2.0 which is almost independent of a radial position and black hole mass. For $\sim 10\%$ of the Eddington rate, the local spectrum emitted from an inner region can be approximated by the diluted blackbody with $f \sim 1.7$. For accretion rates lower than 1% of the Eddington limit, the local spectrum cannot be fitted with any f. For accretion rates close to the Eddington limit, f increases with an increase of α in an inner region for $\alpha > 0.1$, and the radial dependence of f also becomes large gradually. We have applied our results to the observations

$\frac{T_{col}}{T_{eff}}$



降着円盤のlocal spectrumが
diluted blackbodyで表される

$$\left(\frac{T_{eff}}{T_{col}}\right)^4 B_\nu(T_{col})$$

$$T_{col} \simeq (1.8\text{–}2.0)\,T_{eff}$$

X-ray eneryg spectra of the standard disk

1. Derive the radial dependence of the optically thick accretion disk temprarure (you may ignore the inner-boundary condition).

2. Using the result above, calculate the observed energy spectrum from the optically thick accretion disk (local emission is assumed to be black body) with the inner disk radius r_{in} and temprature T_{in} at the distance d and the inclination angle i.

3. Calculate the lumionosity of the accretion disk (local emission is blackbody) with the inner disk radius (r_{in}) and temprature (T_{in}).

4.Let's assume that the optically thick disk emits at the Eddington luminosity, and the inner disk radius (rin) is determined by ISCO of the non-rotating black hole (3*Rs*).
Derive the mass dependence of the inner-disk temperature (Tin). Is the temperature higher or lower when the mass gets higher?

5. Compare the disk temperatures for AGN ($M=10^8 M_\odot$), neutron star ($M=1M_\odot$) and black hole ($M=10M_\odot$), when they are emitting at their Eddington limits?

6. What if the local emission is "diluted blackbody", instead of blackbody?

Observation of the standard disk

THE ASTROPHYSICAL JOURNAL LETTERS, 718:L117–L121, 2010 August 1 doi:10.1088/2041-8205/718/2/L117

THE CONSTANT INNER-DISK RADIUS OF LMC X-3: A BASIS FOR MEASURING BLACK HOLE SPIN

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ABSTRACT

The black hole binary system LMC X-3 has been observed by virtually every X-ray mission since the inception of X-ray astronomy. Among the persistent sources, LMC X-3 is uniquely both habitually soft and highly variable. Using a fully relativistic accretion disk model, we analyze hundreds of spectra collected during eight X-ray missions that span 26 years. For a selected sample of 391 *RXTE* spectra, we find that to within ≈2% the inner radius of the accretion disk is constant over time and unaffected by source variability. Even considering an ensemble of eight X-ray missions, we find consistent values of the radius to within ≈4%–6%. Our results provide strong evidence for the existence of a fixed inner-disk radius. The only reasonable inference is that this radius is closely associated with the general relativistic innermost stable circular orbit. Our findings establish a firm foundation for the measurement of black hole spin.

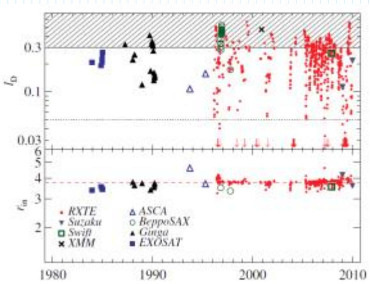

Figure 1. Top: accretion disk luminosity in Eddington-scaled units ($M = 10\ M_\odot$) vs. time for all the data considered in this study (766 spectra). Red arrows show *RXTE* data which are off scale. Data in the unshaded region satisfy our thin-disk selection criterion ($H/R < 0.1$, which implies $l_D < 0.3$; McClintock et al. 2006). The dotted line indicates the lower luminosity threshold (5% L_{Edd}) adopted in Section 3.1. Bottom: values of the dimensionless inner-disk radius r_{in} are shown for thin-disk data in the top panel that meet all of our selection criteria (411 spectra; see Section 3.1). Despite large variations in luminosity, r_{in} remains constant to within ≈4% over time. The median value for the *RXTE* data alone ($r_{in} = 3.77$) is shown as a red dashed line.

Mon. Not. R. Astron. Soc. **347**, 885–894 (2004)

Black hole accretion discs: reality confronts theory

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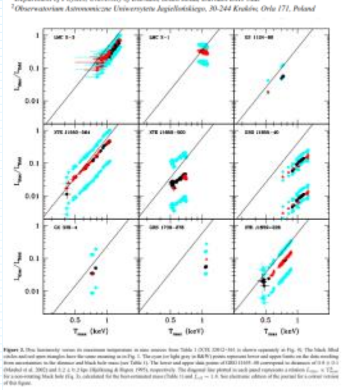

The Astrophysical Journal, 597:780–797, 2003 November 10

ACCRETION DISK SPECTRA OF ULTRALUMINOUS X-RAY SOURCES IN NEARBY SPIRAL GALAXIES AND GALACTIC SUPERLUMINAL JET SOURCES

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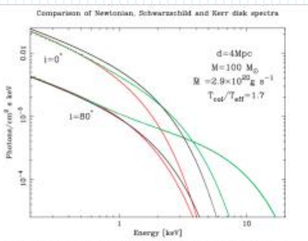

Fig. 1.— Comparison of Newtonian (black), Schwarzschild (red) and extreme Kerr (a = 0.998; green) disk spectra for the face-on (i = 0°) and a near edge-on disk (i = 80°). Inner disk radius is 6 r_g for the Newtonian and Schwarzschild disks, and 1.24 r_g for the Kerr disk. The same mass accretion rate 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).

How to determine the black hole spin from X-ray observaion of the accretiondisk?

IOP Publishing | Classical and Quantum Gravity
Class. Quantum Grav. 28 (2011) 114009 (17pp) | doi:10.1088/0264-9381/28/11/114009

Measuring the spins of accreting black holes

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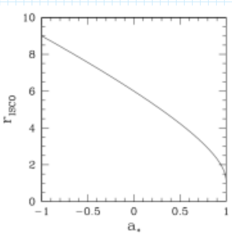


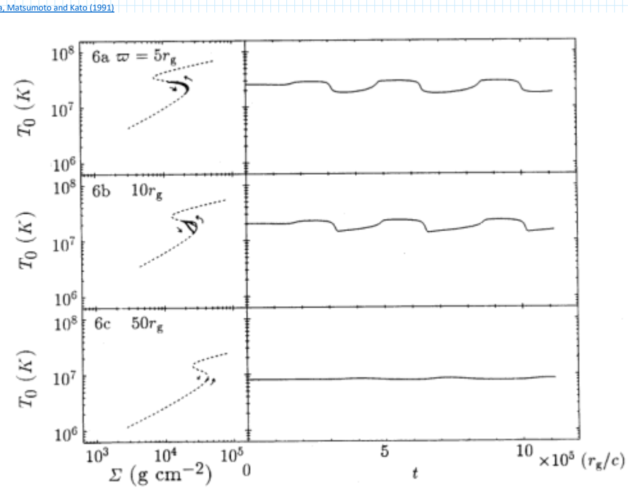
Figure 2. Radius of the ISCO in units of GM/c^2 versus the black hole spin parameter. Negative values of a_* correspond to retrograde motion, with the black hole spinning in the opposite sense of the disk. Stellar black holes are expected to have prograde spins ($a_* > 0$) as a consequence of their formation in a binary system, whereas the spins of supermassive black holes, which are conditioned by galaxy merger events, may be either prograde or retrograde (e.g., Garofalo *et al* 2010).

Table 1. Spin results to date for eight black holes[a].

	Source	Spin a_*	Reference
1	GRS 1915+105	>0.98	McClintock *et al* 2006
2	LMC X-1	$0.92^{+0.05}_{-0.07}$	Gou *et al* 2009
4	M33 X-7	0.84 ± 0.05	Liu *et al* 2008, 2010
3	4U 1543−47	0.80 ± 0.05	Shafee *et al* 2006
5	GRO J1655−40	0.70 ± 0.05	Shafee *et al* 2006
6	XTE J1550−564	$0.34^{+0.20}_{-0.28}$	Steiner *et al* 2010b
7	LMC X-3	<0.3[b]	Davis *et al* 2006
8	A0620−00	0.12 ± 0.18	Gou *et al* 2010

[a] Errors are quoted at the 68% level of confidence.
[b] Provisional result pending improved measurements of M and i.

Observation of the slim disk
Honma, Matsumoto and Kato (1991)



[Yamaoka, Ueda and Inoue (2001)]

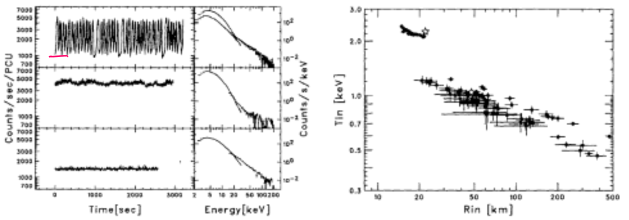


Figure 1. Left panel: Typical PCA light curves and its corresponding energy spectra obtained by the PCA and the HEXTE. Right panel: Relation between $R_{\rm in}$ and $T_{\rm in}$ in the MCD component. Al the pointing observations we analyzed are plotted. The flaring and the queiescent states of the variable states are marked by open stars.

Energy spectra from the "slim disk"

1. Indicate that the slim disk luminosity may exceed the Eddington limit.

2.How the slim disk spectral shape is characterized compared to that of the standard disk?

PASJ: Publ. Astron. Soc. Japan 52, 133–141 (2000)

Galactic Black-Hole Candidates Shining at the Eddington Luminosity

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Abstract

We discuss distinctive features of luminous accretion disks shining at the Eddington luminosity in the context of galactic black-hole candidates (GBCs). We first note that the standard-disk picture is not applicable, although it is often postulated. Rather, the disk becomes advection-dominated while remaining optically thick (the so-called slim disk). The slim disk exhibits several noteworthy signatures: (1) The disk luminosity is insensitive to the mass-flow rate, $\dot{M}$, and is always kept around the Eddington luminosity, $L_{\rm E}$, even if $\dot{M}$ greatly exceeds $L_{\rm E}/c^2$. This reflects the fact that radiative cooling is no longer balanced by viscous heating and excess energy is carried by accreting matter to black holes. (2) The spectra of the slim disks are multi-color blackbody characterized by (i) a high maximum temperature, $kT_{\rm in}$ ~ a few keV, (ii) a small size of an emitting region, $r_{\rm in} < 3r_{\rm g}$ (with $r_{\rm g}$ being Schwarzschild radius), due to substantial radiation coming out from inside $3r_{\rm g}$, and (iii) flatter spectra in the soft-X bands, $\nu S_\nu \propto \nu^0$, because of a flatter effective temperature profile of the slim disk, $T_{\rm eff} \propto r^{-1/2}$ (in contrast with $T_{\rm eff} \propto r^{-3/4}$ in the standard disk). That is, a small $r_{\rm in}(< 3r_{\rm g})$ does not necessarily mean the presence of a Kerr hole. Furthermore, (3) as $\dot{M}$ increases, $T_{\rm in}$ increases, while $r_{\rm in}$ decreases as $r_{\rm in} \propto (T_{\rm in})^{-1}$ approximately. That is, the changes in $r_{\rm in}$ derived from the fitting do not necessarily mean the changes in the physical boundary of the optically thick portions of the disk. Observational implications are discussed in relation to binary jet sources.

Key words: accretion, accretion disks — black holes — stars: X-rays

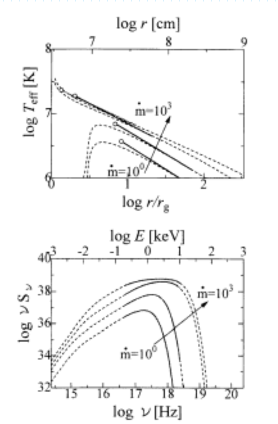
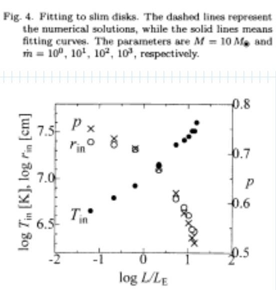


Fig. 4. Fitting to slim disks. The dashed lines represent the numerical solutions, while the solid lines means fitting curves. The parameters are $M = 10\,M_\odot$ and $\dot{m} = 10^0$, 10^1, 10^2, 10^3, respectively.



3.Show examples of the X-ray sources where the slim disk spectra are observed.

[Kubota and Makishima (2004)]

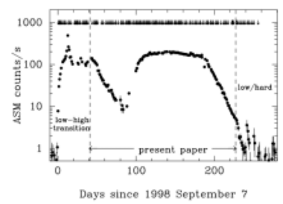
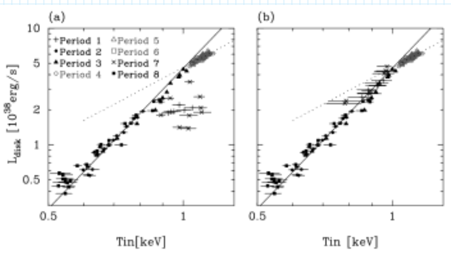


FIG. 1.—Plot of the 1.5–12 keV light curve of XTE J1550−564, obtained with the *RXTE* ASM. The pointing observations are indicated with downward-pointing arrows. The horizontal arrow represents the period studied in the present paper.



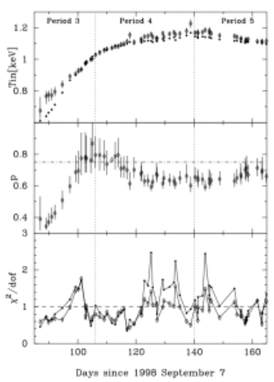


FIG. 7.—Time histories of the best-fit parameters of the *p*-free disk model (*diamonds*). For comparison, the MCD parameters are also plotted with filled circles in the top and bottom panels. In the middle panel, $p = 0.75$ is indicated by a dotted line.

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A STELLAR-MASS BLACK HOLE IN THE ULTRALUMINOUS X-RAY SOURCE M82 X-1?

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ABSTRACT

We have analyzed the archival *XMM-Newton* data of the bright ultraluminous X-ray source M82 X-1 with a 105 ks exposure when the source was in the steady state. Thanks to the high photon statistics from the large effective area and long exposure, we were able to discriminate different X-ray continuum spectral models. Neither the standard accretion disk model [where the radial dependency of the disk effective temperature is $T(r) \propto r^{-3/4}$] nor a power-law model gives a satisfactory fit. In fact, observed curvature of the M82 X-1 spectrum was just between those of the two models. When the exponent of the radial dependence [p in $T(r) \propto r^{-p}$] of the disk temperature is allowed to be free, we obtained $p = 0.61^{+0.03}_{-0.02}$. Such a reduction of p from the standard value $\frac{3}{4}$ under extremely high mass accretion rates is predicted from the accretion disk theory as a consequence of the radial energy advection. Thus, the accretion disk in M82 X-1 is considered to be in the *slim-disk* state, where an optically thick advection-dominated accretion flow is taking place. We have applied a theoretical slim-disk spectral model to M82 X-1 and estimated the black hole mass ≈19–32 $M_{\odot}$. We propose that M82 X-1 is a relatively massive stellar black hole that has been produced through evolution of an extremely massive star, shining at a super-Eddington luminosity by several times the Eddington limit.

Subject headings: accretion, accretion disks — black hole physics — X-rays: individual (M82 X-1)

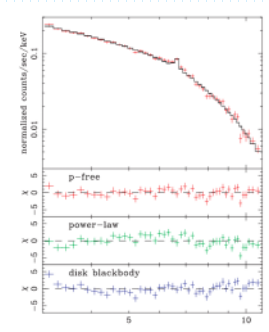

FIG. 1.—Folded spectrum of M82 X-1, fitted with the *p*-free disk blackbody and narrow Gaussian model (*top*), and residuals for fitting with three different models: *p*-free, power-law, and disk blackbody.