Theoretical Interpretation of X-ray Spectra from Active Galactic Nuclei and Low/Hard State of X-ray Binaries with an Accretion Disk-Corona Model

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Abstract

In explaining the spectral properties of active galactic nuclei (AGNs) and X-ray binaries, it is often assumed that they consists of a geometrically thin, optically thick disk and hot, optically thin corona surrounding the thin disk. As for a model of a corona, we adopt the simulation data of three-dimensional MHD accretion flows, while for a thin disk we assume a standard disk. We perform Monte Carlo radiative transfer simulations in the corona, taking into account the Compton scattering of the soft photons from the thin disk by hot thermal electrons. We can reproduce the emergent spectra which are consistent with those of typical Seyfert galaxies, and we also find the rapid time variability in X-ray emission spectra, originating from the density fluctuation in the corona.

Key words: accretion disk — black hole physics — radiative transfer — X-ray : general

1. Introduction

Accreting black holes, such as active galactic nuclei (AGNs) and black hole binaries (BHBs) during their very-high spectral state [state with luminosities around a few tenths of the Eddington limit ($L_{\rm Edd}$)], show the radiation spectra dominated by two components; the thermal bump in UV/soft X-ray band and the power-law emission with a spectral index of $\alpha \sim 1$ in the X-ray band (possibly with a high energy cutoff around MeV). These components are often explained by the disk-corona model (Liang & Price 1977; Bisnovatyi-Kogan & Blinnikov 1977; Haardt & Maraschi 1991, 1993). In this model, the accretion flow consists of geometrically thin, optically thick accretion disk whose structure is studied by Shakura & Sunyaev (1973), and hot, optically thin corona surrounding the disk. The thermal bump is believed as the thermal emission from the optically thick disk, and the power-law component is interpreted to be formed by photons which are emitted from the disk and Compton up-scattered by hot electrons in the corona. So far, however, most of theoretical corona models assume that the coronal structure is steady in time and then the spectral energy distribution is also steady. Such feature cannot explain the highly time-variable spectral behavior of accreting black holes.

In this study, we adopted the three-dimensional simulation data of radiatively inefficient accretion flows (RIAFs) by Kato et al. (2004, hereafter KMS04) as a model of the corona, and calculate for the first time the emergent spectra of disk-corona accretion flow systems. We assume that the optically thick, geometrically thin disk is embedded in the corona, and that this disk is emitting soft photons with thermal spectrum. We perform three-dimensional Monte Carlo radiative transfer simulations to properly calculate the radiation processes and the emergent spectra predicted from this disk corona model (for the detail see Kawanaka et al. 2008).

2. Model and Calculation Method

KMS04 investigated the evolution of a torus threaded by weak localized poloidal magnetic fields by performing the three-dimensional MHD simulation. The simulated MHD flow has almost steady structure, but is slightly oscillating because of the turbulence driven by MRI, and geometrically thick density distribution is produced. In this quasi-steady accretion flow, the density profile is $\rho \propto r$ in the inner part ($r < 20 r_{\rm S}$), while æ$\rho \propto r^{?1}$ in the outer part ($r > 20r$S) (see Fig. 4 in KMS04). In the MHD simulations with no radiative loss the density is given as non-dimensional number $\bar{\rho}$æ with the normalization factor ρ_0, which is treated a free parameter in our calculation. As for the electron temperature T_e, we can evaluate that through the energy balance of the electrons between Coulomb collisions with ions and radiative cooling via inverse Compton scattering.

In calculating the radiative cooling rate of coronal electrons as well as the radiation spectra from the disk-corona system, we set the standard disk (Shakura & Sunyaev 1973) on the equatorial plane in the simulated coronal flow artificially, and solve the radiative transfer using the Monte Carlo simulation (Pozdnyakov et al. 1977). In the following calculations, we set $r_{\rm in} = 3r_{\rm S}$, $\dot{M}_{\rm disk} = 10^{-3}\dot{M}_{\rm Edd}$, and the mass of the black hole to be $M = 10^8 M_\odot$ for AGNs and $M = 20M_\odot$ for X-ray binaries.

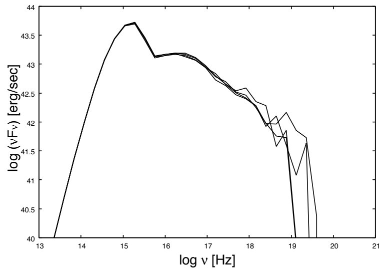

Fig. 1. Spectral variation of the Comptonized emission predicted from the standard disk with a MHD coronal flow around a black hole of $10^8 M_\odot$. Here we set the density parameter as $1.6\times10^{-14}{\rm gcm}^{-3}$.

3. Results and Discussions

Due to the limitation of the space, here we only present the results of AGNs. We show the emergent spectra from the accretion disk with MHD coronal flow with the density parameter $\rho_0 = 1.6 \times 10^{-14}$g cm^{-3} for the corona in Fig. 1. This spectral variation caused by the time variation of MHD coronal flow structure. As for the soft X-ray band (with log $\nu \simeq 17 - 18$) where the spectra show a smooth power-law shape, the spectral index slightly changes with time, and then the X-ray flux fluctuates a little. According to the MHD simulation on which our radiative transfer calculations are based, the three-dimensional structure of the coronal accretion flow is fluctuating everywhere in each timestep. On the other hand, the spectral index depends on the distribution of the Compton y-parameter of the corona. So we can conclude that the fluctuations of the spectral indices of the computed spectra in Fig. 1 reflect the fluctuation of y, which comes from the density fluctuations (which is supposed to be due to MRI) in the coronal flow. Here we find the significant variability of the power-law component of the X-ray emission. The flux of this component predicted from our model changes by a few tens of percent on timescales of the orbital period near the last stable orbit, which is about $10^3(M/10^8M_\odot)$sec. This variability comes purely from the fluctuation of the coronal flow around $r \sim 20r_{\rm S}$, where the scattering optical depth of the coronal flow attains its largest value in its structure. This fluctuation is driven by the turbulence as a result of MRI.

The Compton y-parameter of the coronal flow has a radial distribution, and so the power-law index of the hard X-ray emission α from our simulated flows cannot be determined uniquely by the famous formula for unsaturated Compton scatterings,

$$\alpha = -\frac{3}{2} + \sqrt{\frac{9}{4} + \frac{4}{y}}. \tag{1}$$

Such a coronal flow can be used for the interpretation of the spectral feature of X-ray binaries in their low/hard state (LHS). Recently, Suzaku revealed the broadband X-ray spectra of black hole binaries such as GRO J1655-40 (Takahashi et al. 2008) and Cyg X-1 (Makishima et al. 2008) and it has been realized that they can be fitted by "double Compton" model. In that model hard X-ray emission is produced in hot Comptonizing corona which has two characteristic optical depths, and the seed photons are provided by a geometrically thin and optically thick disk. The fact that two coronal components which have different optical depths implies that the corona has a spatial distribution in the optical depth. These features are well reproduced in our corona model. As for the spectral variability, the observed spectrum becomes softer in the high flux phase, which implies the lower coronal temperature, and the underlying disk is supposed to remain unchanged. The coronal temperature should be lowered if Compton upscatterings occur efficiently and vice versa, so this observation can be interpreted as follows: X-ray luminosity varies solely because of the oscillation in the Comptonizing coronal flow while the underlying disk which emits seed photons into the corona does not need to vary. This interpretation is fully consistent with our corona model.

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