New Spectral State of Supercritical Accretion Flow with Comptonizing Outflow

– Application to Bright ULXs –

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Abstract

Supercritical accretion flows inevitably produce radiation-pressure driven outflows, which will Compton up-scatter soft photons from the underlying accretion flow, thereby making hard emission. We performed two dimensional radiation hydrodynamic simulations of supercritical accretion flows and outflows, incorporating such Compton scattering effects, and demonstrate that there appears a new hard spectral state "Comptonizing outflow state" at higher photon luminosities than that of the slim-disk state. In this state, as the photon luminosity increases, the photon index decreases and the fraction of the hard emission increases.The Compton y-parameter is of the order of unity (and thus the photon index will be ~ 2) when the apparent photon luminosity is $\sim 30 L_{\rm E}$ (with $L_{\rm E}$ being the Eddington luminosity) for nearly face-on sources. This explains the fact that brighter ULXs possess harder X-ray spectra (Berghea et al. 2008). Furthermore, expected SED of the Comptonizing outflow state is consistent with that of the ultraluminous state, which consists of the disk and the cool, optically thick corona (Gladstone et al. 2009).

Key words: accretion, accretion disks — black hole physics — hydrodynamics — radiative transfer

1. Introduction

Ultraluminous X-ray sources (ULXs), which are found in the off-center region of nearby external galaxies, show both the soft thermal and the hard power-law spectra Notably, the typical photon luminosities of ULXs range $L_{\rm ph} \simeq 10^{39-41}$ erg s^{-1}, which exceeds the Eddington luminosity for neutron stars and stellar-mass black holes. There are two possible models considered to account for such large photon luminosities: subcritical accretion (i.e., accretion below the Eddington accretion rate) onto an intermediate-mass black hole (IMBH) and supercritical accretion onto a stellar-mass black hole. Since the black hole masses of ULXs are poorly known, we cannot discriminate these two models at present.

An interesting trend has been reported recently. Berghea et al. (2008) found that the brighter ULXs have harder spectra, whose photon index is $\Gamma < 1.7$. It is also shown that "ultraluminous state",which consists of a disk and cool, optically thick corona, can explain the hard spectra of brighter ULXs with supercritical accretion flow around a stellar-mass black hole (Gladstone et al. 2009). From another theoretical point of view, this luminous and hard accretion state seems to be a naturally explained: supercritical accretion flows inevitably produce radiation-pressure driven outflows and such outflows will Compton up-scatter the soft photons, thereby making a hard emission component. The higher the photon luminosity is, the harder emission we expect. In this proceedings we will demonstrate that new spectral state "Comptonizing outflow state" is indeed feasible based on new two-dimensional radiation-hydrodynamic (RHD) simulations, which incorporate the Compton scattering effects.

2. Numerical Methods

Following Ohsuga et al. (2005), but also considering the effects of Compton scattering in the energy exchange between photons and electrons, we solve the RHD equations in spherical coordinates (r, θ, ϕ). The radiative transfer equation is solved using the flux-limited diffusion approximation (Levermore & Pomraning 1981). The general relativistic effects are incorporated by a pseudo-Newtonian potential (Paczyńsky & Witta 1980). The

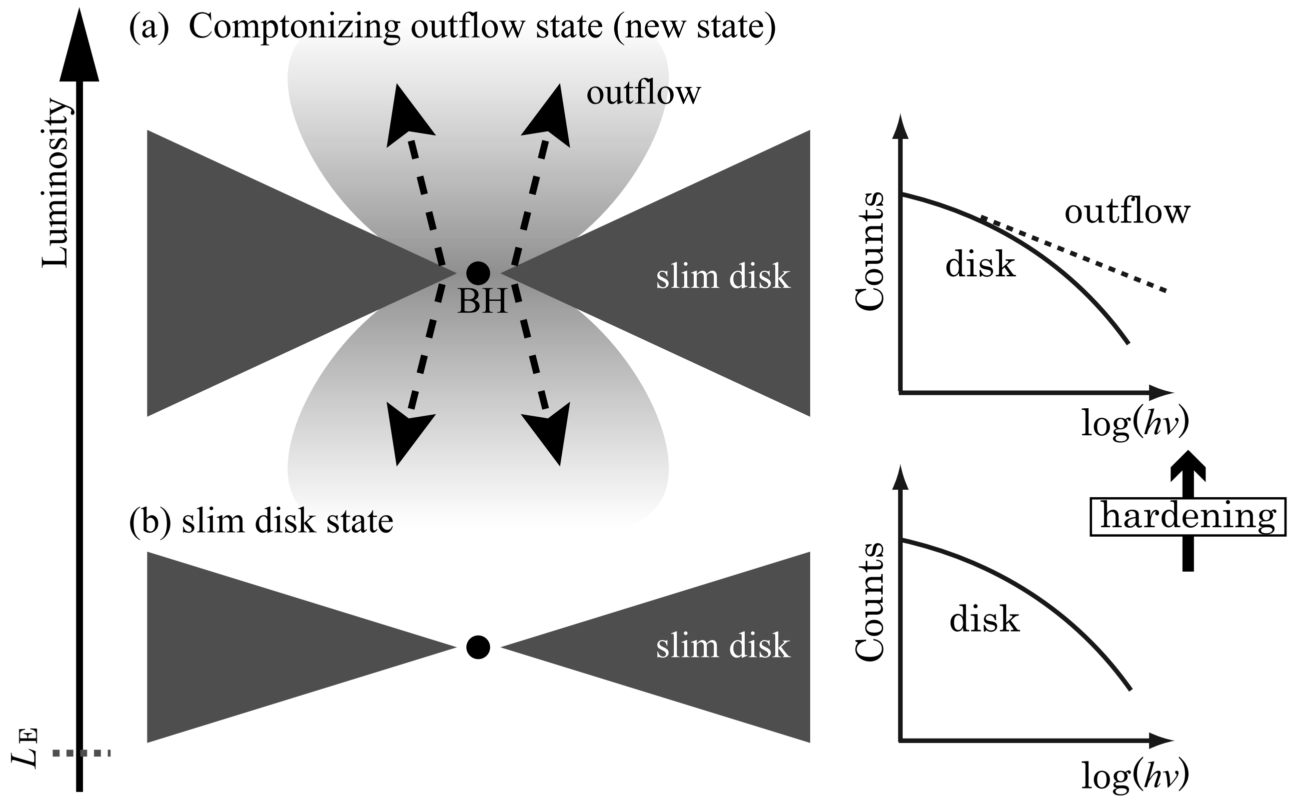

Fig. 1. Schematic pictures of the states of super-Eddington accretion disks: (a) Comptonizing outflow state, which consists of supercritical accretion flows (i.e., slim disks) and Comptonizing outflows, and (b) slim disk state. The SED of the new state is harder than that of the slim disk state, because the new state includes a mildly hot outflow which up-scatters seed photons from the underlying disk.

mass of the black hole is set to $10M_\odot$. We assume that the flow is non-self gravitating, axisymmetric with respect to the rotation axis (i.e., $\partial/\partial\phi = 0$), and symmetric relative to the equatorial plane (where $\theta = \pi/2$). We also adopt the α viscosity prescription (Shakura & Sunyaev 1973) and set $\alpha = 0.1$. The basic equations and numerical model are reported in Kawashima et al. (2009).

3. Spectral Hardness and New Spectral State

We calculated Compton y-parameter of the radiatively driven outflow by using simulation data to discuss the spectral properties of supercritical accretion flows with various accretion rate. We found that as the photon luminosity increases, Compton y-parameter also increases. Especially, y-parameter exceeds 1 when isotropic photon luminosity reaches $\sim 30L_\mathrm{E}$. This is because the larger mass accretion rate is, the more outflow is driven, and, hence, the larger becomes the Thomson optical depth in the outflow region. The electron temperature of the outflow is $10^{7.5-8}$ K and is not significantly affected by mass accretion rate. When an isotropic luminosity is $\sim 30L_\mathrm{E}$, the number of scattering becomes $\sim$100 and, therefore, $y \sim 1$. See Kawashima et al. (2009) for more detail.

We expect that a hard spectral state exists in the supercritical regimes for the supercritical accretion model for ULXs (i.e., central black holes are stellar-mass black holes) to be viable. In this new supercritical state (Comptonizing outflow state), higher photon luminosities correspond to harder SEDs, in analogy to black hole binaries in the very high state, but at even higher photon luminosities (Fig. 1). The presence of Comptonizing outflow state is consistent with the fact that brighter ULXs possess harder X-ray spectra (Berghea et al. 2008). Furthermore, expected SED of the Comptonizing outflow state agrees well with that of the ultraluminous state, which consists of the disk and the cool, optically thick corona (Gladstone et al. 2009).

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