Observational Signatures of Super-Eddington Accretors:
Views from Radiation Hydrodynamics/Radiation Transfer Simulations

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Chapter 1: General Introduction

Super-Eddington accretors exhibit various kinds of unique observational signatures. In this thesis, we study their unique radiation properties by performing radiation hydrodynamic (RHD) and transfer simulations.

Accreting black holes are known to exhibit various luminous and energetic phenomena in the universe. This is made possible, because they extract enormous energy from accreting material and/or utilize the rotation energy of the black holes themselves. Among various types of astrophysical black holes super-Eddington (or super-critical) accretors have attracted much attention recently, since they can produce extremely large luminosities and strong outflow so that their power should give great impacts to their environments. Super-Eddington accretors are thus suggested to play essential roles in yielding various active phenomena e.g., relativistic baryon jets and huge ionized nebulae. It is, hence, of great importance to investigate the basic processes, as well as their observational signatures, of the super-Eddington accretion flow and associated outflow. Such study will be beneficial also for understanding how supermassive black holes have grown up and what influence they should have given to their host galaxies.

Here, we pay particular attention to the enigmatic objects called Ultra-Luminous X-ray Sources (ULXs) successively discovered in nearby active galaxies. The ULXs are off-nuclear point sources producing very large X-ray luminosity ($L_{\rm X} \gtrsim 10^{39}{\rm erg~s^{-1}}$). Since their luminosities exceed the Eddington luminosity of a stellar mass black hole ($L_{\rm Edd} \sim 10^{39}$ erg s^{-1} for the black hole mass of $M_{\rm BH} = 10M_\odot$), there are two major scenarios that have been proposed to explain their nature: (1) hosting an intermediate mass black hole (IMBH) accreting at sub-Eddington rates, and (2) hosting a stellar mass black hole accreting at super-Eddington rates $\dot{M} > \dot{M}_{\rm Edd} \equiv L_{\rm Edd}/c^2$.There are pros and cons for each of these scenarios. The most serious problem for the IMBH scenario is that it is difficult to form a black hole heavier than $100M_\odot$ in the stellar evolutionary models. Although it has been suggested that the IMBH can be formed in dense globular clusters or in stellar evolution of very massive star in the early universe, the detailed processes are still unknown.

In addition to ULXs, we also pay particular attention to another type of enigmatic objects called ultra-luminous supersoft sources (ULSs) which were recently discovered and are extensively studied.They produce very high X-ray luminosities ($L_{\rm X} \gtrsim 10^{39}{\rm erg~s^{-1}}$)

similarly to the ULXs, but nevertheless their X-ray spectra are very soft and is thus distinct from those of the ULXs. More precisely, they are characterized by exhibiting blackbody-like spectra whose blackbody temperature is less than 0.1 keV.Because of their very high luminosities (above the Eddington luminosity of stellar mass black holes), ULSs are also considered to be either super-Eddington sources hosting stellar mass black holes or sub-Eddington sources hosting intermediate mass black holes. A unified scheme is phenomenologically suggested from some observational facts, in which the ULSs are super-Eddington accretion systems accreting at high Eddington rate about $10^3\dot{M}_{\rm Edd}$ viewed from large polar angles of 20-90°.

In view of such diversity in possible super-Eddington objects we perform more extensive and systematic study of super-Eddington accretors to clarify their observational signatures for a variety of mass accretion rates and of viewing angles. Here we address the following key questions:

- How large can the accretion rate and luminosity grow?
- How do the observable quantities (luminosity, kinetic luminosity, outflow rate, etc) depend on the accretion rate?
- How do the spectral properties vary with inclination angles?
- What kinds of (long-term and short-term) spectral variations are expected?

To answer to these questions, we perform two-dimensional axisymmetric radiation hydrodynamic/transfer simulations by taking into account thermal Compton scattering effects, and discuss the unique properties of super-Eddington accretion flow.

Chapter 2: Radiation hydrodynamic simulations of a super-Eddington accretor as a model for ultra-luminous sources

We first perform two-dimensional RHD simulations of super-Eddington accretion flow and the accompanying outflow to investigate how they will be observed from various viewing directions. We consider gas flow around a 10 $M_\odot$ black hole for a mass injection rates of $\dot{M}_{\rm inj}/\dot{M}_{\rm Edd} = 10^2$,$10^3$, and 10^4 (in the unit of $\dot{M}_{\rm Edd} \equiv L_{\rm Edd}/c^2$ with $L_{\rm Edd}$ and c being the Eddington luminosity and the speed of light, respectively), and solve gas dynamics and radiation transfer around the black hole, taking into account inverse-Compton scattering. We confirm a tendency that the higher the mass accretion rate is, the larger the relative importance of outflow over accretion flow becomes. The observational appearance of the super-Eddington flow is distinct, depending whether it is viewed from the edge-on direction or from the face-on direction. This is because nearly edge-on observers can only see the outer cooler ($\sim 10^6$ K) surface of the inner vertically inflated part of the flow. Observational properties are briefly discussed in the context of the ULXs, the extreme ULXs (E-ULXs), and the ultra-luminous supersoft sources (ULSs). We find that the extremely high luminosities of E-ULXs ($L \sim 10^{41}$ erg s^{-1}) can be explained when the flow onto the black hole with $\gtrsim 20M_\odot$ with a very high accretion rate, $\dot{m}_{\rm acc}$ ($\equiv \dot{M}_{\rm acc}/\dot{M}_{\rm Edd}$) $\gtrsim 10^3$, is observed from the nearly face-on direction. The high luminosity $\sim 10^{39}$ erg s^{-1} and the very soft blackbody-like spectra with temperatures around 0.1 keV, as are observed in the ULSs, can be explained, if the super-Eddington flow with $\dot{m}_{\rm acc} \sim 10^2 - 10^3$, is viewed from large viewing angles, $\theta \gtrsim 30°$.

Chapter 3: Variability of Comptonized X-ray Spectra of Super-Eddington Accretor: Approach by Boltzmann Radiation Transport

Next, we investigate the radiation fields around the super-Eddington accretion flow, in which multiple inverse-Compton scattering plays a principal role, by using a newly developed code of the Boltzmann radiation transfer in the Schwarzschild space-time. We apply this code to the post-processing spectral calculations based on the general relativistic, radiation-magnetohydrodynamic simulation data to obtain X-ray spectra seen from various viewing angles. The radiation fields are distinctively separated to a funnel region with an opening angle of $\sim 30^\circ$, which is full with hot (with gas temperature of $T > 10^8$ K), tenuous and high-velocity plasmas, and surrounding cooler (with $T \sim 10^7$ K) and optically thick outflow regions. Accordingly, there is a clear tendency that the smaller the viewing angle is, the harder become the spectra. In particular, hard photons with several tens of keV are observable only by observers at the viewing angles less than $\sim 30^\circ$, consistent with past spectral studies based on the simulations. Further, we investigate how the spectra vary by a flare occurring at the innermost region, finding that the variation amplitude grows as the photon energy increases and that the harder photons emerge more quickly than softer photons. The observational implications on the long-term spectral variability of Ultra-Luminous X-ray sources are briefly discussed.

Chapter 4: Summary and Future Issues

In this thesis we mainly investigate the observational properties of the super-Eddington accretion flow via numerical simulations. Here is the summary:

- The structure of the super-Eddington flow can be decomposed to three parts: relatively cool and dense disk region with a scale height of $H \sim r$, optically thick and relatively slow ($\sim 0.1c$) outflow region, and a jet funnel filled with high-velocity tenuous hot gas ($T_{\rm gas} \gtrsim 10^9 K$).
- Hard radiation is mostly generated within the jet funnel region. The opening angle of the funnel is about 30°.
- The disk spectrum becomes softer as the accretion rate increases. This trend can be easily understood in term of the $\dot{M}$-dependence of the photon trapping radius ($r_{\rm trap} \propto \dot{M}$), i.e. from $4\pi r_{\rm trap}^2 \sigma_{\rm SB} T_{\rm eff}^4 = L_{\rm Edd}$, we have $T_{\rm eff} \propto \dot{M}^{-1/2}$.
- The angular dependence of the observed spectra, especially in the hard X-ray, clearly reflects the structure of the jet funnel, and thus the larger the viewing angle is, the softer the spectrum becomes.
- The ULXs and ULSs are the same objects but seen from different viewing angles: ULXs are more face-on objects, while ULSs are more edge-on objects. The critical viewing angle, which separate ULXs and ULS depend on $\dot{M}$.
- Flares occurring in the innermost region can be a good probe to investigate the funnel structure, and to estimate the viewing angle and accretion rate, since the variation of hard X-ray photons is sensitive to those values.

There are some remaining future issues, such as solving radiation and fluid consistently, the impact of black hole spins, the effect of induced scattering, and considering more distant accretion disks.

The work in this thesis is established by the numerical calculations, the analysis and code development of some parts of Boltzmann solver done by the author and the discussions with co-authors.