Photon Spectra of Super-Critical Black Hole Accretion Flows

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Supercritical Accretion Flows

- spherical accretion: sub-Eddington $L \leq L_E$ ($L_E$: Eddington luminosity)
- disk accretion: anisotropic radiation → supercritical accretion is feasible → super-Eddington $L \gtrsim L_E$
- candidates:
  - powerful jet sources (SS433, S26)
  - Narrow Line Seyfert I, OVV quasars,
  - microquasar (GRS1915+105),
  - ultraluminous X-ray sources
• ULXs are observed in off-center region of nearby galaxies.
• Luminosity: \( L_X = 10^{39-41}\,[\text{erg}\cdot\text{s}^{-1}] \) > \( L_E \) for stellar-mass BHs

(A) subcritically accreting intermediate mass BH?  
or  
(B) supercritically accreting stellar-mass BH?

# Recently, the discovery of a supercritically accreting NS (M82 X-2) has been reported (Bachetti et al. 2014)

ULXs show spectral features different with galactic BHCs nor AGNs.

Studies of SEDS are expected to be a key to understand ULXs.
ULXs show the hard power-law component, which (1) rolls over around 5 keV or (2) extends up to 10 keV.

# The data are kindly sent to us by Dr. Gladstone.

Rad-HD simulations are needed to study super-Eddington Flows.
Structure of Super-Critical Accretion Flow with Compton-Cooled Outflow (Axisymmetric 2D Rad-HD Simulation, $M_{\text{BH}} = 10M_{\odot}$)

(a) $\log T_{\text{gas}}[K]$ vs $\log \rho[\text{g/cm}^3]$ with mildly hot ($10^8 K$), sub-relativistic funnel jet, cool ($10^{6.5} K$), dense and slow ($< 10^{-2}c$) outflow

(b) $\log T_{\text{gas}}[K]$ vs $\log \rho[\text{g/cm}^3]$ with shock-heated region ($10^8 K$), rad. pressure dominant disk
Rad-HD simulation
\[ \rho, T_{\text{gas}}, \nu \]
solve the photon transport using Monte-Carlo method

1. Identify surface where \( \tau_{\text{eff}} = 10 \)
2. generate seed photon from a point above the surface obtained by step (1)
   ✤ consider bremss. emission
   ✤ Taking into account special relativistic effects (Doppler shift & aberration due to bulk motion)
3. Solve photon transport by using Monte-Carlo method
   ✤ free-free absorption
   ✤ photon-trapping effect
   ✤ thermal & bulk Comptonization

output SED
Effect of Compton Scattering on SED

- Thermal and bulk Comptonization harden SEDs.
- In the hot plasma formed near the BH, the photons are upscattered by thermal inverse Compton scattering.

\[ \dot{M} \approx 200L_E/c^2 \]
When the mass accretion rate is lower, the power-law extending up to 20 keV appears.

When the mass accretion rate is higher, rollover at 5 keV appears.

- short range power-law, which is flatter than that of SADM

\[ \dot{M} \approx 10^3 \frac{L_E}{c^2} \]  
\[ 5 \times 10^2 \frac{L_E}{c^2} \]  
\[ 2 \times 10^2 \frac{L_E}{c^2} \]
Dependence of SEDs on the viewing angle “i”

- When the viewing angle is smaller, SEDs become harder.
- For $\dot{M} \approx 2 \times 10^2 L_E/c^2$, the rollover around 5keV also appears when the viewing angle is large.
Spectral Softening in the Outflow

Comptonization in the outflow is forbidden artificially.

\[ \dot{M} \approx 2 \times 10^2 L_E/c^2 \]

When \( \dot{M} \) is higher or inclination angle is larger, SEDs become softer. This is because more of observable photons are Compton downscattered in the cool outflow.

\[ \dot{M} \approx 10^3 L_E/c^2 \]
Structure of Super-Eddington Accretion Flow & Trajectories of Photons

- **high luminosity**
  - hard spectrum
  - $\gtrsim 10$ keV

- **low luminosity**
  - soft spectrum
  - $\lesssim 1$ keV

- sub-relativistic, mildly hot funnel jet

- cool, dense, and slow outflow

- shock-heated region

- radiation pressure dominant disk

- hot coronal inflows upscatter the photons (i.e., inverse-Compton scattering).

- cool coronal outflows downscatter the photons (i.e., Compton scattering)
Comparison with ULXs

- colored curves: calculated spectra
- black points: XMM-Newton Data corrected for absorption (provided by Dr. Gladstone)

Calculated SEDs are similar to those of ULXs! (rollover at 5keV, power-low shape)

However, the soft excess are not reproduced in our simulations, because the emission from $\sqrt{x^2 + y^2} \geq 100 r_s$ is too weak to significantly contribute to the SEDs. ← Larger simulation box containing larger outflowing photosphere may solve this problem. And/or the effects of the magnetic dissipation may be important.
A little more about the spectral state of ULXs

• Variability of SEDs of soft state and dim hard state seems to be explained by our numerical model.

• Bright hard state (cyan) is, however, hard to be explained by our model. **We need more sophisticated theoretical models!**
Second Topic: Where is the hot corona formed

3-dim. **General Relativistic** Radiation MHD simulation

non rotating BH.
initially poloidal magnetic field
Development of GR radiative transfer code

- The accumulation of the poloidal magnetic fields threading the spinning BH results in the formation of the hot corona in the vicinity of the BH. (Takahashi et al. in prep.)

- I am now developing the GR radiative transfer code to calculate the more sophisticated SEDs of black hole accretion flows!

**spin a = 0.99M**

**spin a = -0.99M**
Discovery of Absorption Line in ULXs?

- Middleton et al. (2014) reported discovery of a blue-shifted absorption line with $v \sim 0.1c$ in NGC 5408 X-1 and NGC6946 X-1, which may be the evidence of the outflow.

- These ULXs show soft X-ray spectra. This indicates that we observe this source with higher inclination angle.

- It is important to theoretically reveal the dependence of the absorption line on the viewing angle.
Summary

- The Compton effects are very important in super-critically accreting black holes.
- Coronal inflow is hot and upstaters the seed disk photons. The upscattered photons are downscattered by the coronal cool outflow and the spectral rollover at ~5keV is formed.
- Super-critical accretion flows onto stellar-mass black holes can explain the spectral features of ULXs.
- The calculations including the effects of GR and line transfer are future work.
- I hopefully think we can apply our numerical methods to the studies of AGNs.
Dependence of Viewing Angle: (2) Luminosity

\[ L_X \text{ for } \dot{M} \approx 10^3 \frac{L_E}{c^2} \]
is lower than that for \[ \dot{M} \approx 5 \times 10^2 \frac{L_E}{c^2} \], partly because more amount of photons are swallowed by BH and partly because \( \tau_{es} \gg 1 \) along the funnel jet for \[ \dot{M} \approx 10^3 \frac{L_E}{c^2} \]

Isotropic luminosity increases when the viewing angle is smaller.
mildly collimated by the thick disk
and mildly beamed by the funnel jet!
gas temperature on the equatorial plane

non-rotating BH

rotating BH (a=0.94)

initially poloidal mag. field (r-θ)

initially toroidal mag. field (φ)

ISCO

high temp. region
Tg >> Tr

low temp. region (in LTE)
Tg = Tr

preliminary result
The gas is overheated near BH in all model.
The deviation starts at a larger radius for the poloidal model than the toroidal model.
The deviation starts from the radius (slightly) larger than the ISCO.