Super-Critical Accretion?

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1. General introduction
2. Slim disk model (simplified model)
3. Observational tests - Case of ULXs
4. Multi-dimensional effects
1. Introduction (background)

There are some objects which seem to undergo super-critical (or super-Eddington) accretion.

- What are ULXs? What are NLS1s?
- What do we know from observations?
- What is key physics in super-critical accretion?
Ultra Luminous X-ray sources (ULXs)


- **Bright ($\sim 10^{40}\text{ erg s}^{-1}$) compact X-ray sources**
  - Successively found in off-center regions of nearby galaxies.
  - If $L < L_E$, black hole mass should be $> 100 M_{\odot}$.

- **Two possibilities**
  - Sub-critical accretion onto intermediate-mass BHs ($M > 100 M_{\odot}$).
  - Super-critical accretion onto stellar-mass BHs ($M \sim 3-30 M_{\odot}$).
Arguments in favor of intermediate-mass BH (IMBH)

- Luminosities sometimes exceed $\sim 10^{40}\text{erg s}^{-1}$ (=LE of 100 $M_{\odot}$)
- Some ULXs show $kT \sim 0.1\text{keV}$, indicating large $M_{\text{BH}} (> 100 M_{\odot})$
Energetics (Newtonian version)

grav. energy: half $\rightarrow$ radiation energy
half $\rightarrow$ rotation energy

That is, $(1/2)E_{\text{grav}} = E_{\text{rad}}$

$$\frac{1}{2} \frac{GM_{\text{BH}}\dot{M}}{r} \approx 2 \pi r^2 \cdot \sigma T_{\text{eff}}^4.$$

For $r \sim 3 r_s$, we have

$$T_{\text{eff}} \sim 10^7 \text{ K} \left( \frac{M_{\text{BH}}}{10 M_{\odot}} \right)^{-1/4} \left( \frac{\dot{M}}{L_E / c^2} \right)^{1/4} \propto M_{\text{BH}}^{-1/4}$$

1 keV for $10 M_{\odot}$ BH, 0.1 keV for $10^5 M_{\odot}$ BH
**Narrow-line Seyfert 1 galaxies (NLS1s)**

- **What are NLS1s?**
  - Narrow “broad lines” (< 2000 km s\(^{-1}\))
  - Seyfert 1 type X-ray features
  - Extreme soft excess & variability

- **Seem to contain less massive BHs**
  - Good analogy with stellar-mass BHs in their very high (large \(L\)) state.
  - High \(T_{bb} \propto M_{\text{BH}}^{-1/4}\) ⇒ large soft excess
  - Small \((GM_{\text{BH}}/R_{\text{BLR}})^{1/2}\) ⇒ narrow line width

- **NLS1s = high \(L/L_{E}\) system**

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Boller et al. (NewA 44, 2000)

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Fig. 1. Spectra in the region of H\(\beta\) of the NLS1 Mrk 42 (center), the Sy1 NGC 3516 (below), and the Sy2 Mrk 1066 (above).
What is the Eddington luminosity?

Spherical accretion system cannot shine at $L > L_E$.

Gravity > rad. pressure

$\Rightarrow GM/r^2 > \kappa F/c \Rightarrow L < L_E = 4\pi CGM/\kappa \quad (\therefore F = L/4\pi r^2)$
Super-Eddington flux \((F > L_E/4\pi r^2)\) is possible in the \(z\)-direction because of radiation anisotropy (!?).

**Disk accretion may achieve \(L > L_E\)**
What is Photon trapping?

Begelman (1978), Ohsuga et al. (2002)

When photon diffusion time, $t_{\text{diff}} \sim H \tau / c$, exceeds accretion time $t_{\text{acc}} \sim r / v_r$, photons are trapped.

$r_{\text{trap}} \sim (\dot{M} c^2 / L_\text{E}) r_s$
2. Slim disk model

Slim disk model was proposed for describing high luminosity flows as an extension of the standard disk.

• What is distinct from the standard disk model?
• What are its observational signatures?
**Slim disk model**

Abramowicz et al. (1988); Watarai et al. (2000)

- **Basics**
  - accretion energy
  - trapped photons
  - This occurs within trapping radius
    \[ r_{\text{trap}} \sim \left( \dot{M}c^2/L_E \right) r_s \]

- **Model**
  - Radially 1-D model with radiation entropy advection
    \[ \nu \Sigma T \frac{d(s_{\text{rad}} + s_{\text{gas}})}{dr} = \frac{9}{4} \nu \Sigma \Omega^2 - \frac{8\sigma T^4}{3\tau} \]

- **Spectrum**
  - \( \tau \gg 1 \rightarrow \) multicolor blackbody but with higher \( T \)
胖盘结构

Mineshige, Manmoto et al. (2002)


\[ \dot{M}/(L_e/c^2) = 1, 10, 10^2, 10^3 \]

\[ M_{\text{BH}} = 10^5 M_{\odot} \]

\[ r_{\text{in}} \sim 3r_s ; T_{\text{eff}} \propto r^{-3/4} \]

\[ r_{\text{in}} \sim r_s ; T_{\text{eff}} \propto r^{-1/2} \]

胖盘的特征
1. 小的内半径
2. 更平缓的温度剖面

Slim-disk signatures

1. small innermost radius
2. flatter temp. profile
What determines the inner edge of a disk?

Watarai & Mineshige (PASJ 55, 959, 2003)

**Classical argument:**
Circular orbits of a test particle become unstable at $r < r_{ms}$ ($= 3 r_s$ for no spin BH)

**Case of slim disk:**
Usual stability analysis cannot apply because of no force balance.

Same is true for ADAF.

The disk inner disk is not always at $r_{in} = r_{ms}$. 
**What determines temp. profile?**

**Standard disk:**

Constant fraction of grav. energy is radiated away.

\[ 2 \cdot \pi r^2 \cdot \sigma T^4 \propto \frac{G M_{BH} \dot{M}}{r} \propto r^{-1} \]

\[ \Rightarrow T_{\text{eff}} \propto r^{-3/4} \]

**Slim disk:**

Fraction of energy which is radiated away decreases inward:

\[ t_{\text{diff}} = t_{\text{acc}} \rightarrow \dot{M} c^2 / L_E \sim r / r_{\text{trap}} \propto r \]

\[ 2 \cdot \pi r^2 \cdot \sigma T^4 \propto \frac{G M_{BH} \dot{M}}{r} \propto r^0 \]

\[ \Rightarrow T_{\text{eff}} \propto r^{-1/2} \]
Disk spectra = multi-color blackbody radiation

Temperature profiles affect spectra

\[ T \propto r^{-p} \Rightarrow F \propto \nu^{3-(2/p)} \]

- standard disk \((p=3/4)\)
  \[ \Rightarrow F \propto \nu^{1/3} \]

- slim disk \((p=1/2)\)
  \[ \Rightarrow F \propto \nu^{-1} \]

(e.g. Kato et al. 1998)
3. **Observational tests:**

*Case of ULXs*

We examined the XMM/Newton data of several ULXs which were suggested to contain intermediate-mass black holes.

- How to test the theory?
- What did we find?
Extended disk-blackbody model

(Mitsuda et al. 1984; Mineshige et al. 1994)

Fitting with superposition of blackbody ($B_\nu$) spectra:

$$F_\nu = \cos i \int_{r_{\text{in}}}^{r_{\text{out}}} B_\nu[T(r)]2\pi r dr; \quad T(r) = T_{\text{in}} \left(\frac{r}{r_{\text{in}}}\right)^{-p}$$

Fitting parameters:

- $T_{\text{in}} = \text{temp. of innermost region (max. temp.)}$
- $r_{\text{in}} = \text{size of the region emitting with } B_\nu(T_{\text{in}})$
- $p = \text{temperature gradient}$

Corrections:

Real inner edge is at $\sim \xi r_{\text{in}}$ with $\xi \sim 0.4$

Higher color temp.; $T_{\text{c}} = \kappa T_{\text{in}}$ with $\kappa \sim 1.7$

$\Rightarrow$ Good fits to the Galactic BBHs with $p=0.75$
Spectral fitting 1. Conventional model

( Roberts et al. 2005)

Fitting with disk blackbody ($p=0.75$) + power-law

We fit XMM-Newton data of several ULXs

⇒ low $T_{\text{in}} \sim 0.2$ keV and photon index of $\Gamma = 1.9$

If we set $r_{\text{in}} \sim 3r_S$, BH mass is $M_{\text{BH}} \sim 300 M_{\odot}$. 

NGC 5204 X-1

log hν

log conts
Problem with DBB+PL fitting

Spectral decomposition of DBB & PL components

DBB comp. is entirely dominated by PL comp.

Can we trust values derived from the minor component?
Model fitting, assuming $T \propto r^{-p}$

We fit the same data but with the extended DBB model

$\Rightarrow$ high $T_{\text{in}} \sim 2.5 \text{ keV}$ and $p=0.50\pm0.03$ (no PL comp.)

$M_{\text{BH}} \sim 12 M_{\odot}$ & $L/L_E \sim 1$, supporting slim disk model.
Why can both models give good fits?

Because the spectral shapes are similar below ~10 keV.

Both show \( f_{\nu} \propto \nu^{-1} \) in 0.1~10 keV range.
Temperature–Luminosity diagram

(Vierdayanti et al. 2006, PASJ 58, 915)

New model fitting gives $M_{BH} < 30M_{\odot}$. Low-temperature results should be re-examined!!

The same test is needed for NLS1s

No evidence of IMBHs so far
Fate of Prad-driven instability

Radiation pressure-dominated SS disk is unstable.

(1) relaxation oscillation?
   Honma et al. (1991),
   Szuszkiewicz & Miller (1998)

(2) soft-to-hard transition?
   Takeuchi & Mineshige (1998),
   Gu & Lu (2000)

(3) strongly clumped disk?
   Krolik (1998)

(4) disk-corona structure?
Bursting behavior of micro-quasar
(Yamaoka, Ueda & Inoue 2002)

GRS 1915+105 exhibits state transitions between peak (slim disk) and valley (thin disk). The time scales are given by $T \propto r^{-1/2}$ for the peak and $T \propto r^{-3/4}$ for the valley.
4. Multi-dimensional effects

The slim-disk model applies only to the flow with $L \sim L_E$. For even higher $L$, we need to perform radiation-hydrodynamical (RHD) simulations.

- What are the multi-dimensional effects?
- What can we understand them?
A simple model


Problem with the slim-disk formulation

Radiative cooling rate is evaluated as $\sim 4 \sigma T^{4/3} \tau$ (at same $r$)

Consider a part of the disk which is moving inward

Dynamics is given. Solve radiation transfer in $z$-direction.

Can approximately evaluate 2D photon trapping effects.
The slim-disk model overestimates the luminosity. The frequency of the SED peak first increases then decreases with increase of mass-accretion rate.

(c) K. Ohsuga
Our 2D RHD simulations


- First simulations of super-critical accretion flows in quasi-steady regimes.
- Matter with 0.45 Keplerian A.M. is continuously added through the outer boundary → disk-outflow structure
- Flux-limited diffusion adopted.
- $\alpha$ viscosity with $\alpha = 0.1$.
- Mass input rate: $1000 (L_E/c^2)$ → luminosity of $\sim 3 L_E$
Overview of 2D super-critical flow


Case of $M=10 M_{\text{sun}}$

& $\dot{M}=1000 L_{\text{E}}/c^2$

(c) K. Ohsuga
Why is accretion possible?


Radiation energy density is high: $E_{\text{rad}} \gg E_E \equiv L_E / 4\pi r^2 c$.

Then why is the radiation pressure force so weak?

Note radiation energy flux is $F_{\text{rad}} \propto (\kappa \rho)^{-1} \nabla E_{\text{rad}}$.

→ Because of high $\rho$ and relatively flat $E_{\text{rad}}$ profile.

Low $\rho$ and steep $E_{\text{rad}}$ profile yields super-Eddington flux.
Photon trapping

\[ F_r = \text{radiation flux in the rest frame} \]

\[ F_0^r = \text{radiation flux in the comoving frame} \]

\[ F_r \approx F_0^r + v_r E_0 \]

Photon trapping also helps reduced radiation pressure force.

Radiation flux (\(F^r\)) is inward!
The observed luminosity is sensitive to the viewing angle; Maximum $L \sim 12 L_E$!!

$4\pi D^2 f(\theta)/L_E$

Our simulations

$\cos \theta$

$\theta/\pi$

Viewing angle

⇒ mild beaming

Why beaming?

Photon energy increases as $\theta$ decreases, why?
- Because we see photons from deeper, hot region.
- Because of Doppler effect.

Why photon number increases as $\theta$ decreases, why?
- Because of anisotropic gas distribution.
- Because $I_\nu / \nu^3$ is Lorentz invariant & $h \nu$ increases.
Future issue
Interaction with magnetic fields

Magnetic fields are essential ingredients in disks

- Photon-bubble instability (Begelman 2002)
- Magnetic tower jet $\rightarrow$ global RHD+MHD simulations necessary

(Kato, SM, & Shibata 2004)
Conclusions

• Near- and super-critical accretion flows seem to occur in some systems (ULXs, NLS1s...?).

• Slim disk model predicts flatter temperature profile. Spectral fitting with variable $p$ proves the presence of supercritical accretion in ULXs. How about NLS1s?

• 2D RHD simulations of super-critical flow show super-Eddington luminosity, significant radiation anisotropy (beaming), high-speed outflow, large absorption, etc. $L$ can be $\sim 10 \ L_E$!!

• Issues: magnetic fields, line spectra, instability,...