(3D) reconnection of super-critical accretion disks in relativistic radiation MHD simulations

Hiroyuki R. Takahashi¹,
K. Ohsuga¹, Y. Sekiguchi² & T. Kawashima¹
1: National Astronomical Observatory of Japan (NAOJ)
2: Toho University
Overview of the Accretion Disks

1. Companion star supplies gas to the black hole through the wind or Roche Lobe overflow.

2. Formation of Accretion Disks
   The gas accretes inward due to the angular momentum transport. Kinetic energy is converted to the magnetic energy through MRI, and the gas is heated by MRX.

3. The gas finally falls onto BH. 
   -> contributes to the BH/spin evolution
   A part of the gas is ejected through the jets / outflow

Black hole accretion disk is powered by liberating the grav. energy. Mass accretion rate is the key parameter determining disk structures.
Thermal balance in Accretion disks

Consider the energy balance of local patch in accretion disks

The energy equation in steady state

\[
\nabla \cdot \left[ \rho \left( e + \frac{p}{\rho} \right) \mathbf{v} \right] - (\mathbf{v} \cdot \nabla) p = q^+ - q^-
\]

Advective energy \quad \text{work by } p

Eq. of thermal balance at radius \( r \)

\[
Q_{\text{adv}}^- = Q_{\text{vis}}^+ - Q_{\text{rad}}^-
\]

\( Q_{\text{vis}}^+ = Q_{\text{adv}}^-: \text{Radiatively Inefficient Accretion Flow} \)

Density is low and radiative cooling can be ignored
Gas pressure dominates radiation pressure
Luminosity is low but its spectrum is hard

\( Q_{\text{vis}}^+ = Q_{\text{rad}}^-: \text{Standard Disks} \)

Density is high and radiative cooling is dominant
Gas pressure dominates the radiation pressure
Luminosity is high but is spectrum is soft

\( Q_{\text{vis}}^+ = Q_{\text{adv}}^-: (\text{Supercritical}) \text{ Slim Disk} \)

Density is very high, but radiative cooling rate is small.
Radiation pressure dominates the gas pressure
Three modes of accretion flow

Radiatively Inefficient Accretion Flow

Standard Disk

Slim Disks

\[ Q^{+}_{\text{vis}} = Q^{-}_{\text{adv}} \]

High temp. / geometrically thick radiative processes can be ignored

\[ Q^{+}_{\text{vis}} = Q^{-}_{\text{rad}} \]

Low temp. / geometrically thin radiative cooling is important

\[ Q^{+}_{\text{vis}} = Q^{-}_{\text{adv}} \]

Rad. pressure dominant radiative cool. & force are important

Mass Accretion Rate

figures from Ohsuga+09
Thermal Balance in Magnetic Reconnection

Knowledge about the accretion disks can be applied to the MRX.

energy balance in MRX

\[ Q_{\text{adv}}^- = Q_{\text{MRX}}^+ - Q_{\text{rad}}^- \]

1. Inflowing Poynting flux

2. Energy dissipation
\[ Q_{\text{MRX}}^+ = n j^2 \]

3. Advective cooling
\[ Q_{\text{adv}}^- = p v A / L \]

4. Radiative cooling
\[ Q_{\text{rad}}^- \]

\[ Q_{\text{MRX}}^+ : \text{heating rate by the magnetic reconnection} \]
\[ Q_{\text{adv}}^- : \text{cooling rate due to the energy transport by outflows} \]
\[ Q_{\text{rad}}^- : \text{cooling rate by the radiative process} \]

Magnetic reconnection models can be classified in three modes.

See also Uzdensky & McKinney ‘11
Purely magnetohydrodynamic MRX $\iff$ RIAF

When radiative cooling can be ignored (but collisional), two types of magnetic reconnection realize even in relativistic plasmas.

**Sweet - Parker type MRX**

**Petschek type MRX**

The Poynting energy is dissipated in the reconnection region, and the energy is transported outward as the thermal and kinetic outflows.

$$Q_{\text{MRX}}^+ = Q_{\text{adv}}^-$$

See also Uzdensky & McKinney '11
Radiative cooling in MRX ⇔ SSD

When the plasma density is relatively high, or the B field is sufficiently strong, the radiative cooling is the dominant source for cooling process.

The gas internal energy is transported outward through the radiative cooling. Then the current sheet cools down and collapses.

The advective cooling would also be important because substantial energy is used to create thermal particles

\[ Q^{+}_{MRX} = Q^-_{rad} + Q^-_{adv} \]

See also Uzdensky & McKinney '11
High density plasma ⇔ Slim Disks

When the plasma density is sufficiently high, the photons cannot escape from the reconnection region due to the scattering with electrons. The liberated energy is once transported to the gas thermal and kinetic energies. The electrons collide with the photons, then the gas is decelerated. The advective cooling is supported by the radiation energy.

\[ Q^+_{MRX} = Q^-_{adv} \]

See also Uzdensky & McKinney '11
Summary of Similarity b/w AD and MRX

**RIAF**
Gas pressure dominant
no radiative cooling

**Standard Disk**
Gas pressure dominant
radiative cooling

**Slim Disks**
rad. pressure dominant
radiative cooling/force important

---

Importance of Radiative Transfer
Mass Accretion Rate

**MHD**
Takahashil+11

**rad. cooling**
Jaroshcek ’09

**p_{rad} dominant**
Takahashil+15

---

There is a similarity between the AD and MRX. When considering the energy dissipation in accretion disks, it would be important to taking into account the radiative process in MRX.

See also Uzdensky & McKinney ’11
Hard X-ray extend to 10keV is observed. The hard X-ray would be originated from Comptonized photons in hot corona. How and where the hot corona is formed?
General Relativistic Radiation MHD

\[ \partial_t \left( \sqrt{-g} \rho u^t \right) + \partial_i \left( \sqrt{-g} \rho u^i \right) = 0 \]

Gauss's law
\[ \partial_i \left( \sqrt{-g} B^i \right) = 0 \]

Induction eq.
\[ \partial_t \left( \sqrt{-g} B^i \right) = -\partial_j \left[ \sqrt{-g} \left( b^j u^i - b^i u^j \right) \right] \]

Energy momentum cons. for MHD
\[ \partial_t \left( \sqrt{-g} T^{t}_{\nu} \right) + \partial_i \left( \sqrt{-g} T^{i}_{\nu} \right) = \sqrt{-g} T^{\kappa}_{\lambda} \Gamma^{\lambda}_{\nu \kappa} + \sqrt{-g} G_{\nu} \]

Energy momentum cons. for radiation
\[ \partial_t \left( \sqrt{-g} R^{t}_{\nu} \right) + \partial_i \left( \sqrt{-g} R^{i}_{\nu} \right) = \sqrt{-g} R^{\kappa}_{\lambda} \Gamma^{\lambda}_{\nu \kappa} - \sqrt{-g} G_{\nu} \]

Radiation four force
\[ G^{\mu} = -\rho (\kappa_{a} + \kappa_{s}) R^{\mu \nu} u_{\nu} - \rho (\kappa_{s} R^{\alpha \beta} u_{\alpha} u_{\beta} + \kappa_{a} 4\pi B) u^{\mu} \]

M1-closure
\[ R^{\mu \nu} = \frac{4}{3} \bar{E} R u^{\mu \nu} R + \frac{1}{3} \bar{E} R g^{\mu \nu} \]

We included general relativity in our SR-RMHD code.
Gravity force is included through the metric metric: Kerr-Schild coordinate (Cowling approximation)
Here we assume ideal MHD.
We consider the free-free emission and electron scattering for the source of opacity.
3D General Relativistic Radiation MHD simulations of Accretion Disks (relatively high mass accretion rate)

jet (~0.3c)

Accretion Disks

B field

10 solar mass Black Hole
Gas temperature at the Equatorial Plane

The gas and rad. are in local thermodynamic equilibrium far from the BH. The gas temperature deviates from the rad. temperature inside $r<15\,r_g$. The deviation radius is larger than the ISCO. These results imply the high temperature corona forms near BH.
Gas temperature on the equatorial plane

- **High mass accretion rate** (high density)
- **(relatively) low mass accretion rate** (low density)

The gas temperature is about $10^7$ K for a larger radius in both cases. The hot (yellow-orange) region exists near the black hole and its temperature is 10-100 times higher than the radiation temperature. As the mass accretion rate decreases, the overheated region extends to a larger radius.
Formation of the hot region

For a larger radius, the inflow time is much longer than the cooling time.
- the gas has sufficient time to be in local thermodynamic equilibrium before accretion.

For a smaller radius, inflow time becomes shorter, and there is no time to be in LTE. Since the cooling time is reciprocal to the gas density, the overheated region is smaller for the higher mass accretion case.

(see, also Sadowski '15)
GR effect: BH spin dependence

Mass accretion rate (and the density) is similar (~L_{edd}/c^2), but the black hole is rapidly rotating (right).

The gas temperature is about $10^7$ K for a larger ($r > 20 \, r_g$) radius in both cases. The overheated (yellow-orange) region exists near the black hole ($r<\sim 10r_g$). These structures are similar, but the maximum temperature is higher for a rapidly rotating case.

-> This indicates that the effect of BH rotation contributes to the disk heating?
Outward Poynting flux

The black hole rotation energy can be extracted through the magnetic field,

\[ F^{(EM)}_{r=r_H} = 2(B^r)^2 \omega r_H (\Omega_H - \omega) \sin^2 \theta \]

BH angular vel.  B field angular vel. Blandford Znajec ’77

Outward radial Poynting flux

Most of the Poynting flux is transported to the outflow region. But the substantial energy is also transported towards the disk region.

non-rotating BH  rotating BH

jet region  disk region

Takahashi+ ’16
Outward Poynting flux

The black hole rotation energy can be extracted through the magnetic field,

\[ F^{(EM)} \bigg|_{r=r_H} = 2(B^r)^2 \omega r_H (\Omega_H - \omega) \sin^2 \theta \]

B field angular vel.  BH angular vel.  Blandford Znajec ’77

energy flux at r=5r_g

non-rotating BH

rotating BH

Schematic view of BH and accretion disk

jet formation

disk heating

turbulent field

Most of the Poynting flux is transported to the outflow region. But the substantial energy is also transported towards the disk region. The outward Poynting flux is larger than the inflowing gas energy flux. The disk can be heated by dissipating the Poynting flux through MRX.  Takahashi+ ’16
Summary

**There are similarity between Accretion disk and MRX**
Accretion disks can be categorized depending on the mass accretion rate.
- **RIAF: viscous heating = advective cooling**
  ⊛ similar to the pure hydrodynamical (kinetic) MRX
- **Standard disks: viscous heating = radiative cooling**
  ⊛ similar to the radiative cooling dominated MRX
- **Slim disks: viscous heating = viscous heating.**
  ⊛ similar to the radiation pressure dominated MRX

We note that it is important to taking into account the radiative effects (for both energy and momentum) to understand the energy dissipation in accretion disks.

**General Relativistic Effects**
  Hot accretion flow forms close to the black hole -> origin of hot corona
  BH rotation energy is transported to the A.D. and it would dissipate through (driven?) MRX or other mechanisms (mode conversion)?