Growth of massive black holes in dusty clouds: impacts of relative velocity between dust and gas

Shohei Ishiki (Hokkaido University), Takashi Okamoto (Hokkaido University), Hidemobu Yajima (Tukuba University)
1. Introduction

- Gas accretion
- SMBH seed $10^5 M_\odot$
1. Introduction

gas accretion

SMBH seed $10^5 M_\odot$
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SMBH seed $10^5 \, M_\odot$

SMBH $10^9 \, M_\odot$

gas accretion
1. Introduction

Gas accretion

SMBH seed
$10^5 \, M_\odot$

$\sim 1 \, \text{Gyr}$
(e.g. Mortlock et al. 2011)

SMBH
$10^9 \, M_\odot$
1. Introduction

- Gas accretion
- Radiation
- SMBH seed $10^5 M_\odot$
- SMBH $10^9 M_\odot$
- $\sim 1$ Gyr
  (e.g. Mortlock et al. 2011)
1. Introduction

- Gas accretion
- Dust
- Radiation

SMBH seed
$10^5 \, M\odot$

$\sim 1 \text{ Gyr}$ (e.g. Mortlock et al. 2011)

SMBH
$10^9 \, M\odot$
1. Introduction

\[ \text{SMBH seed} \quad 10^5 \, M_\odot \]

\[ \text{gas accretion} \]

\[ \text{dust} \]

\[ \text{radiation} \]

\[ \sim 1 \text{Gyr} \]

\[ (\text{e.g. Mortlock et al. 2011}) \]

\[ \text{SMBH} \quad 10^9 \, M_\odot \]
1. Introduction

Extinction curve of quasar at z=6.2

Maiolino et al. (2004)
1. Introduction

Extinction curve of quasar at $z=6.2$

Existence of dust around SMBH in the early universe

Maiolino et al. (2004)
Chapter 1. Introduction

1D radiation hydrodynamics

Yajima et al. (2017) shows that radiation pressure suppress the dusty gas accretion onto BH.
1. Introduction

Yajima et al. (2017) assumed that dust and gas are completely coupled.
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The effect of relative velocity between dust and gas
1. Introduction
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We investigate the impacts of relative motion of dust and gas on the accretion rate onto BH
2. Method & Model
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1D radiation hydrodynamics
2. Method & Model

1D radiation hydrodynamics

IMBH

\[ M_{\text{BH}} = 10^5 M_\odot \]
2. Method & Model

1D radiation hydrodynamics

IMBH

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

H, He, Graphite;

\[ n_H = 10, 30, 100 \, \text{cm}^{-3} \]
2. Method & Model

- 1D radiation hydrodynamics

- IMBH: $M_{BH} = 10^5 M_☉$

- H, He, Graphite; $n_H = 10, 30, 100 \text{ cm}^{-3}$

- Relative velocity between dust and gas (Ishiki et al. 2018)
2. Method
2. Method

1D radiation transfer
2. Method

1D radiation transfer

1D Hydrodynamics (Ishiki et al. 2018)

<table>
<thead>
<tr>
<th>scheme:</th>
<th>SLAU2 (Kitayama &amp; Shima 2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dust drag force:</td>
<td>Coulomb drag force</td>
</tr>
<tr>
<td></td>
<td>Collisional drag force</td>
</tr>
<tr>
<td></td>
<td>(Draine &amp; Salpeter 1979)</td>
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</tbody>
</table>

| dust charge:   | primary electron emission      |
|               | Augar electron emission        |
|               | secondary electron emission    |
|               | electron and ion collision     |
|               | (Weingartner & Draine 2001),   |
|               | (Weingartner et al. 2006)      |
2. Method

Dust
2. Method

Dust

Graphite
## 2. Method

<table>
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<tr>
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2. Method
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Chemical reactions

Collisional ionization
Recombination
Dielectronic recombination
2. Method

Chemical reactions
- Collisional ionization
- Recombination
- Dielectronic recombination

Heating and cooling
- photoionization heating
- collisional ionization cooling
- dielectronic recombination cooling
- collisional excitation cooling
- bremsstrahlung cooling
- inverse Compton cooling
3. Result

density: 10, 30, 100 cm\(^{-3}\)
BH mass: \(10^5 \, M_\odot\)
\(\eta (L = \eta \dot{M} c^2)\): 0.1, 0.3
Z: 0.1, 1.0 Z_\odot
Dust-to-metal: solar
3. Result  Time averaged BH luminosity

\[ L = \eta \dot{M} c^2 \]

\[ \eta = 0.3 \quad \eta = 0.1 \]

Red: relative velocity
Black: completely coupled

Time averaged BH Luminosity
Eddington Luminosity

Number density of gas
3. Result  Time averaged BH luminosity

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-Time averaged BH Luminosity  
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The decoupling of dust from gas promotes the gas accretion onto BH.
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Time averaged BH Luminosity
Eddington Luminosity

The decoupling of dust from gas promotes the gas accretion onto BH.
3. Result

Why does the decoupling of dust from gas promote the gas accretion onto BH?
3. Result

Spatial distribution of dust grains

- $n_H = 100 \text{ cm}^{-3}$, $Z = 1.0 \ Z_\odot, \eta = 0.1$
- $n_H = 10 \text{ cm}^{-3}$, $Z = 1.0 \ Z_\odot, \eta = 0.1$
- $n_H = 100 \text{ cm}^{-3}$, $Z = 1.0 \ Z_\odot, \eta = 0.3$

![Graph showing spatial distribution of dust grains with gas and dust concentrations at $t=5.0$ Myr.](image)
3. Result Spatial distribution of dust grains

\[ n_H = 100 \text{ cm}^{-3}, \quad Z = 1.0 \, Z_\odot, \eta = 0.1 \]
\[ n_H = 10 \text{ cm}^{-3}, \quad Z = 1.0 \, Z_\odot, \eta = 0.1 \]
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Dust-to-gas mass ratio near BH becomes small.
3. Result  Spatial distribution of dust grains

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The effect of radiation pressure on dusty gas accretion becomes weaker.
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Red: relative velocity  
Black: completely coupled

Time averaged BH Luminosity  
Eddington Luminosity

Number density of gas
3. Result  Time averaged BH luminosity

Red: relative velocity
Black: completely coupled
Blue: analytical estimate Z=1.0 Z☉
Green: analytical estimate Z=0.1 Z☉
Gray: analytical estimate Z=0.0 Z☉

Time averaged BH Luminosity
Eddington Luminosity

\[ L = \eta \dot{M} c^2 \]
\[ \eta = 0.3 \quad \eta = 0.1 \]
3. Result  Time averaged BH luminosity

Red: relative velocity
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Blue: analytical estimate $Z=1.0 \, Z\odot$
Green: analytical estimate $Z=0.1 \, Z\odot$
Gray: analytical estimate $Z=0.0 \, Z\odot$

$L = \eta \dot{M} c^2$

$\eta = 0.3 \quad \eta = 0.1$

Time averaged BH Luminosity
Eddington Luminosity

Analytical estimate shows almost same accretion rate between $\eta = 0.1, Z = 0.1 \, Z\odot$ and $\eta = 0.1, Z = 0.0 \, Z\odot$. 

Number density of gas
3. Result

How about Spectral Energy Distribution (SED) at IR wavelengths?
3. Result

Temperature of dust: Radiative equilibrium
3. Result  SED: IR re-emission from dust

\[ n_H = 100 \text{ cm}^{-3}, \]
\[ Z = 1.0 Z_\odot, \eta = 0.3 \]

Dust Temperature

- Gas
- Dust 0.1 micron
- Dust 0.01 micron

Magenta: Relative velocity
Black: Initial dust-to-gas mass ratio

\( \sim 10^3 \text{ K} \)

SED
3. Result SED: IR re-emission from dust

\[ n_H = 100 \text{ cm}^{-3}, \]
\[ Z = 1.0 Z_\odot, \eta = 0.3 \]

Dust Temperature

\[ \sim 10^3 \text{ K} \]

Radiation pressure removes high temperature dust.
4. Summary

• The decoupling of dust from gas promote the gas accretion onto BH.
• The dust-to-gas mass ratio significantly changes in HII regions because of the strong radiation pressure.
• The decoupling of dust from gas affects SED at IR wavelengths.
3. Result  Spatial distribution of dust grains

\[ n_H = 100 \text{ cm}^{-3}, \]
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gas
dust 0.1 micron
dust 0.01 micron

\( t=5.0 \text{ Myr} \)