Bulge-driven and Radiation-regulated Growth of Seed Black Holes

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TCAN (Theoretical and Computational Astrophysics Network) Collaboration
Observation

Quasars at high-z
BH mass $\sim 10^8 - 10^9 \, M_{\odot}$

Fan+ 01,03
Willot+ 03,10
Mortlock +11
Wu+ 15
• **Seed BH mass**
  – $10^2$- $10^5 \, M_\odot$

• **Formation scenarios**
  – Pop III remnant
  – Direct collapse
  – Stellar collapses

• **Accreting at Eddington rate**

Volonteri 12
Natarajan 11
How do we estimate an accretion rate onto a BH?

Bondi Accretion (1952)

Eddington-limited Bondi-Hoyle rate
Radiative Feedback by Black Hole

H II region
(Hot & Ionized)
\(\eta = 0.1, \ M_{bh} = 100 \ M_{\text{sun}}, \ T_{\text{inf}} = 10^4 \ K, \ n_H = 10^6 \ cm^{-3}\)
**Accretion regimes**

*Mode I*, *Mode II*, super-Eddington

- Different accretion regimes as a function of BH mass & Gas density are main parameters
  - **Mode I**: ~1 percent of Bondi rate, 5-6 orders of difference between max/min accretion rates
  - **Mode II**: Eddington-limited, 1-2 orders of mag difference between max/min accretion rates.
  - **super-Eddington**: at high $M_{BH}$ and $n_H$

- Low accretion rate: only ~1 percent of Bondi rate
- Only the gravitational potential of a BH was considered....

Park & Ricotti (2012)
Bulge can boost accretion?

- Accretion Radius
- Strömgren Radius
- Effective Bondi Radius
  - Due to bulge comp
Effective Bondi radius
increased Bondi radius due to bulge

\[ |\Phi| = \frac{GM(<r)}{r} \text{ (km}^2\text{s}^{-2}) \]

\[ \frac{GM_{BH}}{r_{B,eff}} \equiv c_\infty \]

- Bulge: Hernquist (1990) profile
- Gas temperature
- BH Mass
Effective Bondi Radius as a function of bulge-to-BH mass ratio

\[ \delta_{\text{bulge-BH}} = \frac{M_{\text{bulge}}}{M_{\text{BH}}} \]

\[ \delta_{\text{crit}} \sim \frac{10^6 M_\odot}{M_{\text{BH}}} \left( \frac{T_\infty}{10^4 \text{ K}} \right)^{3/2} \]

Park et al. (2015) to be submitted
Simulations w/o Radiative Feedback

- $T=10^6$ K
- $M_{BH} = 10^6 M_\odot$

- Accretion rate makes a transition at $\delta_{\text{bulge-BH}} \sim 10^3$

Park et al. (2015) to be submitted
Simulations w/o Radiative Feedback
Accretion rates

\[ \delta_{\text{crit}} \sim \frac{10^6 M_\odot}{M_{\text{BH}}} \left( \frac{T_\infty}{10^4 \text{K}} \right)^{3/2} \]

\[ \dot{M}_{\text{BH}} = \dot{M}_B \left( \frac{r_{B,\text{eff}}}{r_B} \right)^\beta \]

\[ \beta \sim 1 \]

Park et al. (2015) to be submitted
Accretion rate as a function of bulge-to-BH ratio with radiative feedback

Park et al. (2015) to be submitted
Simulations with radiative feedback

\[ \delta_{\text{crit}} \sim \frac{10^6 M_\odot}{M_{\text{BH}}} \left( \frac{T_\infty}{10^4 \text{ K}} \right)^{3/2} \]

- \( \delta_{\text{crit}} \): same with non-radiative simulations
- Accretion rate is suppressed by 2 orders of mag
The radial velocity profiles show a more distinct changes as a function of radius for M6N1 with different bulge-to-BH mass ratios. However, with the various bulge components (first columns). However, the simulations are consistent with our model.

The radial velocity increases as approximately effective accretion radius when the Str¨omgren sphere, which leads the accretion to grow by this timescale describes how fast BHs grow by timescale for $\tau_x \equiv \frac{10^{-x} M_{\text{bulge}}}{(1 - \eta) \dot{M}_{\text{BH}}}$. The mean accretion rates do not change as a function of BH mass as $\tau_1$ is not sensitive to $10^2 M_\odot$, the accretion rate remains the same since $10^6 M_\odot$, and the mean accretion rates do change as a function of the bulge mass. The bottom panel of Figure 7 shows the time-averaged density (top), temperature (middle), and radial velocity (bottom) profiles as a function of radius for $M_{\text{BH}} = 10^6 M_\odot$, the accretion behavior displays a distinct difference. The density inside $\bar{r}_{\text{crit}} = 10^5$ is found (shown as a solid line) as the non-radiative accretion onto a heavy seed produces $\tau_2 \equiv 10^{-x} \frac{M_{\text{bulge}}}{(1 - \eta) \dot{M}_{\text{BH}}}$. The density inside $\bar{r}_{\text{crit}} = 10^3$ is comparable to the mean size of the Str¨omgren sphere. However, the outflow weakens with increasing $\bar{r}_{\text{crit}} = 10^4$...
Transition of Accretion Regimes

\[ \dot{M}_{\text{BH}} = \dot{M}_B \left( \frac{r_{\text{B,eff}}}{r_B} \right)^\beta \]

Park et al. (2015) to be submitted
Summary

• **Bulge-driven accretion**
  – the massive bulge increase $r_{B,\text{eff}}$, but only when $\delta_{\text{bulge-BH}} > \delta_{\text{crit}}$.
  – A minimum bulge mass?
    • $\sim 10^6 M_\odot$

\[
\delta_{\text{crit}} \sim \frac{10^6 M_\odot}{M_{\text{BH}}} \left( \frac{T_\infty}{10^4 \text{ K}} \right)^{3/2}
\]

\[
\dot{M}_{\text{BH}} = \dot{M}_B \left( \frac{r_{B,\text{eff}}}{r_B} \right)^\beta
\]

• **Radiation-regulated accretion**
  – Light seed ($\sim 100 M_\odot$) : $\delta_{\text{crit}} \sim 10^4$
    • hard to grow
  – Heavy seeds ($> 10^5 M_\odot$) : $\delta_{\text{crit}} \sim 1$
    • likely to grow coevally with bulge
Summary

Light seeds (< $10^2 \, M_{\text{Sun}}$)

Heavy seeds (> $10^5 \, M_{\text{Sun}}$)

Bulge-driven growth

$M_{\text{BH}}$-sigma?