Observational Constraints on the Growth of Supermassive Black Holes at the Edge of the Universe

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Origin of the Black Hole

Black holes with $\sim 10 \ M_{\odot}$
Supermassive Black Holes (SMBH)

- **What are they?**
  - Black Holes with masses $\sim 10^5 - 10^{10} \, M_\odot$

- **Where are they?**
  - Centers of massive spheroids/bulges or quasars

Elliptical galaxy

Bulges of Spirals

Quasars/AGNs
Super-massive Black Holes in Inactive Galaxies

SMBH mass $\propto$ mass, velocity dispersion, and luminosity of the host galaxy (e.g., Gebhardt et al. 2000; Ferrarese & Merritt 2000; Marconi & Hunt 2003)

But why?
Which was born first?
When did the massive SMBHs appear?

Quasars (Active galaxies)

- Quasars = QUASi-stellAR radio sources
- $10^{12} \, L_\odot$ in a sphere with $d < 2.5 \times 10^{17} \text{ cm}$ (3 light-months) $\Rightarrow$ powered by SMBHs!

Im, Lee, et al. 2007,
Lee, Im, et al. 2008
Reverberation Mapping or Single Epoch Measurement

Black Hole Mass: $M = f R v^2 / G$

Line luminosity

Line width

Emission line

Flux

Wavelength

Continuum

Variability in the Central Light Source

Time Lag = Distance to BL Clouds

Variability in the Line Flux

Width of the Emission Line Due to Doppler Motion = Velocity of BL Clouds
Single Epoch Measurement

- Reverberation mapping \(\rightarrow\) Long-term monitoring needed (months – decades)

- \(R_{\text{BLR}} \propto L(\text{Continuum})\) or Line Flux
  \(\rightarrow\) BH measurement with a single-epoch spectrum is possible! (Kaspi et al. 2000; Vestergaard et al. 2005; Greene & Ho 2005; Kim, Im, & Kim 2010)

\[
M_{\text{BH}} = \left(2.0^{+0.4}_{-0.3}\right) \times 10^6 \left(\frac{L_{\text{H}\alpha}}{10^{42}\text{ ergs s}^{-1}}\right)^{0.55 \pm 0.02} \left(\frac{\text{FWHM}_{\text{H}\alpha}}{10^3\text{ km s}^{-1}}\right)^{2.06 \pm 0.06} \, M_\odot
\]
Masses of SMBHs at high redshift

- The most massive SMBHs ($M \sim 10^{10} M_\odot$ or more) at $2 < z < 4.5$, $10^9 M_\odot$ BHs at $z \sim 6.42$ ($t_{\text{univ}} < 1 \text{ Gyr}$)

Shen et al. (2007), Also see Vestergaard et al. (2008)

A few more points here from ground-based NIR spectroscopy (Jiang et al.; Kurk et al. 2007)
• Quasars have been discovered out to $z \sim 6.43$ (Fan et al. 2003; Willott et al. 2007).

Luminous quasars exist out to $z \sim 6.4 \rightarrow 10^9 \, M_\odot$ SMBHs in place at $t_{\text{univ}} \sim 1$ Gyr

QSO at $z=6.43$ (Willott et al. 2007)
Growing SMBHs

- \( M(t) = M(0) \exp\left[\frac{(1-\epsilon)}{\epsilon} \frac{t}{t_{\text{Edd}}}\right] = M(0) \exp\left(\frac{t}{\tau}\right) \), with \( \tau \approx 4.5 \times 10^7 (\epsilon/0.1) \) yrs

- Not enough time (only \(~0.64\) Gyr between \(z=6\) and 15)

- Previous measurements with CIV and MgII \(\rightarrow\) Prone to errors, Better if we can use H\(\alpha\) or H\(\beta\)
Need for Better Mass Measurement

- Reliability of CIV measurement has been in question (or even MgII – outflow contribution, asymmetric profile, etc)
- At higher z, metal abundance may decrease + extinction
- Need for a well-calibrated, independent measure of $M_{BH}$ using optical spectra such as Hα or Hβ (e.g., Greene & Ho 2005).
AKARI Spectroscopy at 2.5 - 5 μm

AKARI is the only facility in the world capable of detecting Balmer lines of QSOs at 3.4 < z < 6.5!

No Spitzer

Low-z

Difficult from the ground

QSong

High-z

Poorly studied

Brα(4.05)  Brβ(2.62)  Paα(1.87)

Observed Wavelength (micron)

Redshift

[OIII]

[OII]

Hα

Hβ

UV line mass estimators

Netzer et al. 2007; Shen et al. 2008

Shen et al. 2008)
QSONG

- **Quasar Spectroscopic Observation with NIR Grism (AKARI Mission Program)**

- NIR Spectroscopic Study of high-z and low-z AGNs at 2.5 – 5.0 μm with NIR grism of AKARI (R ~ 120, FWHM ~ 2500 km/sec)

- High-z study (HQSONG): 200+ QSOs at 3.4 < z < 6.42

- Low-z study (LQSONG): 102 nearby AGNs + red AGNs
High-z QSONG Sample (HQSONG)

- 200+ Type-1 QSOs at $3.4 < z < 6.4$ (mostly SDSS QSOs)

- z-band magnitude limit:
  $z_{AB} < \sim 19$ for $z < 5.5$
  $z_{AB} < \sim 20$ for $z > 5.5$

- $L_{bol}$ limit $\sim 10^{47}$ erg s$^{-1}$
- $M_{BH}$ limit $\sim 10^9 M_\odot$

- BH mass from well-calibrated Hα line (Greene & Ho 2005; McGill et al. 2008; versus CIV/MgII) $\rightarrow$ evolution of the most massive QSOs at high-z
NIR Prism Observation
BR 0006-6224 (z=4.51)
Pilot Study: Hα lines of 14 QSOs at 4.5 < z < 6.22

- z = 4.69
- z = 5.59
- z = 4.97
- z = 5.80
**SDSS J 114816+525150 at z=6.42**

![Graph of Hα emission line spectrum with wavelength in microns on the x-axis and flux in mJy on the y-axis. The graph shows a prominent Hα line with redshifted features.]
**Ha Detections (NP)**

- $z = 6.07$
- $z = 6.13$
- $z = 6.22$

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2010 November 4-6
SMBH Mass Evolution

- $10^{9.3} - 10^{10.1} \, M_{\odot}$ \(\Rightarrow\) A few $10^9 \, M_{\odot}$ SMBHs existed at $z \sim 6$ (0.95 Gyr)

- $L_{\text{bol}}/L_{\text{Edd}} \sim 0.4 - 1.8$ [0.8] \(\Rightarrow\) Eddington-limited accretion

- No $M \sim 10^{10} \, M_{\odot}$ SMBHs at $z > \sim 6$ ($t_{\text{univ}} \sim 0.9$ Gyr) - they are growing!

AKARI points (Im et al.)
How should they evolve?

- Accretion at Eddington limit
- Dustless quasars (Jiang et al. 2010)

\[ M(t) = M(0) \exp\left[\frac{(1-\epsilon)}{\epsilon} \left(\frac{t}{t_{\text{Edd}}}\right)\right] = M(0) \exp\left(\frac{t}{\tau}\right), \text{ with } \tau \approx 4.5 \times 10^7 \left(\frac{\epsilon}{0.1}\right) \text{ yrs} \]

- $10^8$ growth $\Rightarrow$ 18 e-fold time $\Rightarrow$ $t \approx 0.8$ Gyr $\sim$ age of the universe
- Luminosity evolution with $L(t) \sim \exp(t/\tau)$
How did SMBHs grew?

- Fast growth from stellar mass BHs
- Slow growth with heavy BH seeds

SDSS (Shen et al. 2008)
AKARI (Im et al. 2010)

$z \sim 5.5$
$z > 6.4$
Infrared Medium-Deep Survey (IMS)

- J-band Imaging over 200 deg$^2$ to ~23 AB mag (+I,z,Y,...) to identify and study z > 6.5 quasars
- Currently, ~55 deg$^2$ covered
- Collaborative agreement with NCU (Taiwan), NASA/GSCF/Pomona College (USA) for GRB study
GRB 100905A at $z \sim 7.5$

- UKIRT zJHK imaging from 15 min after the burst (Im et al. 2010, GCN Circular 11222)
- $z$-dropout at redshift $\sim 7.5$
- Third of three GRBs with short duration
Quasars at $z \sim 7$?

Z-dropout Candidate (30'' x 30'')

$i$ $z$ $Y$ $J$ $3.6\mu m$ $4.5\mu m$

Composit QSO Spectrum of $z=7.5$
BC2003 with SSP, $Z=0.02$, Salpeter IMF & $t=1Gyr$ of $z=1.5$
Brown Dwarf Model Spectra of $T=1200K$
Current Limit: Luminosity Evolution
(z > 6.5)

- \( L \sim \exp[t/\tau(\varepsilon)] \)
- Radiation eff. \( \varepsilon \sim 0.1-0.3 \)
Summary

• QSONG: AKARI NIR (2.5-5 micron) Spectroscopy Study of ~200 high redshift QSOs (3.4 < z < 6.4) and 102 low redshift AGNs

• Rest-frame optical spectra for high redshift QSOs – Evolution of mass of SMBHs at high redshift – first detection of Hα lines at QSOs z > 4.5 (before JWST)

• There are ~10⁹ M⊙ SMBHs out to z ~ 6, but the most massive QSOs (10¹⁰ M⊙) disappears beyond z ~ 6

• Limit on number density of quasars at z > 6.5