Lecture 3. Quasars as First Light Probes: Reionization and Galaxy/SMBH Co-Evolution

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The First Quasar Discovered $z=0.158$ (1963)

1964: Quasar 3C9 ($z=2.01$) discovered
first detection of Ly alpha emission
Gunn-Peterson Effect

- Gunn and Peterson (1965)
  - “It is observed that the continuum of the source continues to the blue of Ly-α (in quasar 3C9, z=2.01)”
  - “only about one part of $5 \times 10^6$ of the total mass at that time could have been in the form of intergalactic neutral hydrogen ”

- After recombination, the universe was neutral (atomic)

- Absence of G-P trough -> the universe highly ionized

- There must be a process of REIONIZATION
Jim Gunn

- an observer: Gunn standard star, Gunn filter
- an instrumentalist: WFPC1, SDSS
- a theorist: Gunn-Peterson effect
- and an extraordinary person
Reionization
Gunn-Peterson Effect

- optical depth along line of sight:

\[ \tau = \int_0^{z_0} n(z)\sigma(\nu(1+z))(dl/dz)dz \]

HI density:

\[ n(z) = n_{HI}(1+z)^3 \]

abs. crossing section:

\[ \sigma = \pi e^2 f / m_e c \]

\[ \tau(z) \approx n_{HI}\sigma(\nu_0(1+z))cH_0^{-1}(1+z)^{3/2} \]

\[ \tau = 6.4 \times 10^5 h^{-1} \left( \frac{\Omega_b h^2}{0.02} \right) \left( \frac{1+z}{3} \right)^{3/2} \left( \frac{n_{HI}}{n_H} \right) \]
Gunn-Peterson Test

- Classic G-P (1965) effect:
  \[ \tau_{GP} \sim 10^5 \left( \frac{n_{HI}}{n_H} \right) \]
  - Saturates at low neutral fraction
Evolution of Lyman alpha forest absorption

$z \approx 0.1$

$z \approx 1.5$

$z \approx 2.5$

$z \approx 4$

$z \approx 5$
First detection of Gunn-Peterson Effect

Becker, XF +2002
Keck/ESI 30min exposure

Gunn-Peterson Trough in z=6.28 Quasar

Keck/ESI 10 hour exposure

White et al. 2003
Evolution of Lyman Absorptions at $z=5-6$

$\Delta z = 0.15$
Accelerated Evolution at $z>5.7$

- **Optical depth evolution accelerated**
  - $z<5.7$: $\tau \sim (1+z)^{4.5}$
  - $z>5.7$: $\tau \sim (1+z)^{11}$
  - *End of reionization?*

XF et al. 2006
Mortlock et al. 2011
G-P optical depth to neutral fraction

• G-P optical depth

\[ \tau = 6.4 \times 10^5 h^{-1} \left( \frac{\Omega_b h^2}{0.02} \right) \left( \frac{1+z}{3} \right)^{3/2} \left( \frac{n_{\text{HI}}}{n_{\text{H}}} \right) \]

• IGM: photoionization, ionization = recombination

\[ n_{\text{HI}} \Gamma = n_{\text{HI}} n_e \alpha(T), \quad \Gamma: \text{photoionization rate} \]
\[ \alpha: \text{recombination coeff.} \]

• Assuming IGM mostly ionized: \( n_{\text{HII}} \sim n_{\text{H}} \)

\[ \tau_{\text{GP}} \propto \frac{(1+z)^6 (\Omega_b h^2)^2 \alpha(T)}{H(z)} \propto \frac{(1+z)^{4.5} (\Omega_b h^2)^2 \alpha(T)}{h \Gamma \Omega_m^{0.5}}. \]

• Finally, IGM is not uniform: use IGM density distribution from simulation..
Evolution of IGM neutral fraction

• From GP optical depth measurement, volume averaged neutral fraction increase by >~ order of magnitude from z~5.5 to 6.2

• at z>6: Gunn-Peterson trough saturates

XF et al. 2006
Voigt line profile: Gaussian core and Lorentzian (damping) wing

\[
\tau = \int_0^{z_0} n(z) \sigma(\nu(1+z))(dl/dz)dz
\]
z~7 quasar: first IGM damping wing?

- substantial damping wing: f(HI) >= 0.1

Mortlock et al. 2011
Gunn-Peterson Damping Wing
in z=7.54 Quasar
Evolution of neutral fraction
Are biggest BHs in the biggest galaxies?

VS.
• In merger driven galaxy evolution sequence, the most luminous quasars are:
  – in the most massive halos
  – have high SFR
  – after the ULIRG/SMG phase
  – providing energy for galaxy feedback through winds/outflows
Co-Evolution of supermassive black holes and galaxies in the early universe

- Needs to measure:
  - BH mass
  - and the properties of quasar host galaxies
Rest-frame UV imaging of high-z quasar host galaxies with HST

- quasars outshine hosts by $>100$
- cosmological surface brightness: $(1+z)^{-4}$
- non reliable detection of stellar light so far

$z=6.42$, HST WFP3

Metchley et al. 2002
Spectral energy distribution

- **UV/optical**: accretion disk
- **mid-infrared**: hot dust and torus
- **far-infrared**: cold dust → host galaxy

![Spectral energy distribution graph](image)
(sub-)mm observations of quasars

Ground-based (sub-)mm observations (ALMA, NOEMA):

- **dust continuum**
  - star-formation (SF) tracer
  - ISM mass
- **[C\text{\(\equiv\)}] 158 \mu m** line
  - main ISM coolant
  - strongest line in FIR
  - SF tracer
- **CO lines:**
  - ISM tracer
  - cold gas supply for SF
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Dust continuum observations

A very large fraction of $z>6$ quasar hosts detected in the FIR

Decarli+ 18
BV+ 18
Properties of $z > 6$ quasar host galaxies

- Sizes around 1 – 3 kpc
- SFRs: 100 – 1500 $M_{\text{sun}}$/yr
- Dust masses: $10^7$ – $10^9 M_{\text{sun}}$
- SFRD: 50 – 400 $M_{\text{sun}}$/yr/kpc$^2$

→ Orion-like SFRDs, over kpc scales
Diversity of the host galaxies of reionization-era quasars environment revealed by ALMA

- Bright submm sources: warm dust -> SFR > 100 solar mass/year
- Bright CO emission: cool gas -> $10^{10}$ solar mass H2 mass
- Enhanced merger rate
- Formation of the most massive galaxies in early universe

Shao et al. 2018
Decarli et al. 2018
Wang et al. 2019
What about host galaxy mass

• assume: dynamical mass = bulge mass
• line and size comes from [CII] or CO
• with rotation curve: fit dynamical model
• without rotation curve: $M \sin(i) \sim \text{FWHM}^2 \times \text{radius}$
Evolution of M-sigma relation?

- \( \frac{M_{\text{BH}}}{M_{\text{dyn}}} \approx 0.002 - 0.05 \)
- local relation: \(~1.4 \times 10^{-3}\)
- average: one order of mag higher ratio at \(z\sim6\) vs. \(z\sim0\)
Caveats

- selection bias: targeting brightest quasar
- uncertainty in black hole mass
- uncertainly in host galaxy dynamical mass
- this is not what simulation shows

- evolution of M-sigma relation still an open question
What we know about high-z quasar evolution and black hole growth

- luminous quasars have been discovered at $z>7$
- they are powered by billion solar mass black holes
- they are among the rarest objects in the universe and their density declines rapidly towards higher redshift
- they are hosted by galaxies with strong star formation activities and abundance molecular gas
- high-z quasar spectra show a rapid increase of neutral hydrogen fraction in the IGM at $z>6$ — end of reionization.
what are the open questions?

• how to push the redshift limit beyond $z \sim 8$
• how to efficiently search for low-luminosity quasars/smaller BHs at $z > 7$
• do we really need massive seed or different accretion mode to grow billion solar mass BHs?
• are hosts of luminous quasars massive? and do they live in dense environment?
• is the IGM about half neutral by $z \sim 7$
summary: three plots to remember