Narrow-line regions in high-redshift AGNs

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Typical UV-optical spectrum of quasars

Composite spectrum of SDSS quasars (Vanden Berk et al. 2001)

Rich emission lines in UV-optical spectra of quasars.

Through the comparisons with photoionization models, gas properties of quasars (density, ionization, metallicity, …) can be diagnosed even at high-z.

Broad emission lines from BLRs

- Very bright, easily detectable even in very high-z quasars
- Various gas-diagnostic studies, especially about metallicity
BLR metallicity

Stacking analysis of SDSS quasar spectra

- No redshift evolution up to $z \sim 6-7$
- Clear $M_{\text{BH}}$-$Z_{\text{BLR}}$ relation
- Probably caused by the mass-metallicity relation of their host galaxies
- But… Why no redshift evolution?

- BLR clouds are in a very compact area around SMBH ($<10$ pc)
- The total BLR gas mass is tiny ($<10^{3} M_{\odot}$)
- BLR may not be a good tracer of the chemical evolution of quasar host galaxies?
- Should we focus on NLRs?
NLR metallicity

- No strong forbidden lines in rest-UV
  → Type 2 AGNs needed for high-z studies
- Not so many known type-2 AGNs at high-z
  → High-z radio galaxies (HzRGs)

57 HzRGs at 1<z<4

- No significant redshift evolution also for NLRs, not only for BLRs
NLR metallicity; a caveat, and this work

A caveat
- Only small number of strong forbidden lines in HzRG spectra
- Difficult to give constraints on ISM parameters simultaneously
  ~ metallicity ($Z_{\text{NLR}}$), ionization parameter ($U$), gas density ($n_H$), …
- Need to assume some important param ($n_H$ in the case below)

This work: Deep spectroscopy \(\rightarrow\) Many faint lines \(\rightarrow\) Diagnostics
Deep spectroscopy of HzRGs with VLT/FORS2

Our VLT/FORS2 data

\[ T_{\text{exp}} = 4 \text{ hr} \]

\[ T_{\text{exp}} = 3 \text{ hr} \]

\[ T_{\text{exp}} = 3 \text{ hr} \]

Supplementary data

- HzRGs at z\( \sim \)2–3
- from the literature
- 15 HzRGs in total

<table>
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<th>Name</th>
<th>( z )</th>
<th>available emission lines</th>
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<td>NVSS J002402−325253</td>
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</table>
Photoionization models

**Cloudy ver.13.03** (Ferland et al. 2013)

- Assuming plane-parallel ionization-bounded clouds
- Metallicity: $0.1 < Z_{NLR}/Z_{sun} < 5.0$ with a 0.1 step
  ~ with the solar elemental abundance ratios, except for He & N
- Ionization parameter: $-3.0 < \log U < -0.5$ with a 0.1 step
  ~ $U = \int_{13.6\text{eV}}^{\infty} \frac{L_\nu}{h\nu} d\nu / 4\pi r^2 n_e c$
- Gas density: $2.0 < \log n_H (\text{cm}^{-3}) < 6.0$ with a 0.1 step
- 53,300 (= 50 x 41 x 26) models in total

**Comparison with observations**

- Using only high-ionization lines (ionization potential > 24 eV)
  ~ SiIV, OIV], NIV], CIV, HeII, CIII], [NeIV]
- Identifying the best model and uncertainty by searching for models with minimum $\chi^2$
Rest-UV multi-line analysis: Results

NLR gas density
- Consistent with previous studies
  \[ \log n_{\text{NLR}} \approx 2 - 5 \text{ (cm}^{-3}) \]
  \[ \text{not well constrained} \]

NLR ionization parameter
- Independent of \( L_{\text{AGN}} \) (mostly const.)
- Inferring a larger NLR in higher \( L_{\text{AGN}} \)
- Consistent with Kaspi’s relation
  \[ r_{\text{NLR}} \propto L_{\text{AGN}}^{0.5} \]

NLR metallicity
- \( Z_{\text{NLR}} \approx 1 - 2 \, Z_{\odot} \)
- Not sub-solar metallicity at \( z \sim 2-3 \)
- Why no metallicity evolution?
  ~ Are young AGNs “obscured” by heavy dusts?
NLR gas density at high-z?

Gas density in high-z star-forming galaxies

- Higher density at higher redshift?
  ~ 1 dex higher at z≈2.3? (Sanders+16)
  ~ due to higher SFR? (Shimakawa+15, Kaasinen+17)

Gas density in NLRs?

- At the local Universe (please see Joh et al.’s poster!!)
  ~ log $n_{\text{NLR}}$ ~ 2.5 (cm$^{-3}$)
  ~ higher than star-forming galaxies at z≈0

- At high redshifts?
  ~ somewhat higher than z≈0?
  ~ not very clear, need further studies
  ~ rest-frame optical spectroscopy
NIR spectroscopy of type-1 quasars with Subaru/MOIRCS

Our Subaru/MOIRCS run

- 5 bright quasars with
  \( \sim i_{AB} \sim 17.7 - 18.5 \) at \( z \sim 3.0 - 3.1 \)
  \( \sim \) selected from SDSS DR7 quasars
- 60 – 80 min. exposures for each target
- Multi forbidden lines detected in 2 objects

Supplementary data

- 5 bright quasars from the literature
  \( \sim i_{AB} \sim 17.2 - 18.5 \) at \( z \sim 3.2 - 3.5 \)
  \( \sim \) with the detection of multi forbidden lines
  \( \sim \) Araki+12 w/ Subaru MOIRCS
  \( \sim \) Zuo+15 w/ Palomar Hale 200 inch tel.
Rest-frame optical diagnostics

**High-z quasars at 3.0<z<3.5**
- 4 [OII]-undetected quasars
- 3 [OII]-detected quasars

**SDSS quasars at 0.4<z<0.8**
- 26 quasars with $L_{5100}>10^{45.7}$
  ~ only [OIII]-detected objects
- Mostly [OII]-detected
- Flux ratios are similar to high-z [OII]-detected quasars

**Photoionization models**
- high-z [OII]-undetected ones are characterized by gas with 1 dex higher density than high-z [OII]-detected quasars and low-z quasars
Rest-frame optical diagnostics

Where are dense gas clouds?
- gas clouds associated in molecular torus? (pc-scale)
- distributed in host galaxies? (kpc-scale)

\[
U = \int_{13.6eV}^{\infty} \frac{L_\nu}{h\nu} \, dv / 4\pi r^2 n_e c
\]

\[
\rightarrow r = \sqrt{\frac{Q(H)}{4\pi n_e c U}}
\]

\[
U = 10^{-3}, n_H = 10^6 \text{ cm}^{-3}, Q(H) \sim 10^{57} \text{ s}^{-1}
\]

\[
\left( Q(H) = \int_{13.6eV}^{2\text{keV}} \frac{L_\nu}{h\nu} \, dv \right)
\]

\[
\rightarrow \log r \sim 2.5 - 3.5 \quad (\text{pc})
\]

- Dense gas at the host scale!
Near-future perspective: Subaru/PFS

Powerful multi-object spectrograph
- 2400 fibers within 1.3 diameter FoV
- $0.38 \, \mu m < \lambda_{obs} < 1.26 \, \mu m$ at once
- Spectroscopic survey will start soon! (2022-)

NLR Diagnostics for statistical samples
- Analyses of the [SII] and BPT diagram up to $z \sim 1$ (see Joh et al.’s poster)
- Analyses on the [OII]-[OIII]-[NeIII] diagram up to $z \sim 1.5$
- Analyses on the rest-UV diagnostics up to very high redshifts
  ~ are there enough interesting targets (high-$z$ type-2 AGNs) for PFS observations?
Near-future perspective: HSC new HzRG sample

- WERGS (Wide and deep exploration of radio galaxies with Subaru HSC; Yamashita+18)
- HSC (dropout selection) + FIRST (21 cm)
- Discovery of a HzRG ($z=4.7$; Yamashita+, submitted)
- ~100 HzRGs in the entire HSC-SSP field
- See Yamashita-san’s talk on Day5

Near-future perspective: HSC-eROSITA collaboration

- FoV 0.83 deg$^2$ with ~15” resolution
- Launched successfully on 13 Jul. 2019
- HSCSSP-eROSITA Collaboration MoU
- 100 deg PV observations have been done
- A few type-2 AGNs per deg$^2$ (Merloni+12)
- HSCSSP will deliver $z_{\text{ph}}$ & morphology
Near-future perspective: **SPICA**

- Why almost no metal-poor AGNs in high-z?
- Obscured heavily by dusts? \(\rightarrow\) **MIR-FIR** AGN surveys needed
- **SPICA**: a ESA-JAXA joint project (ESA M5 candidate)
  \(~ 2.5m cooled (8K) IR space telescope (10 \(\mu\)m < \(\lambda\) < 230 \(\mu\)m)\)

from the **SPICA M5 proposal**

- Herschel (80K) \(\rightarrow\) **SPICA** (8K)
- x100 deeper sensitivity

- **MIR diagnostics**: \([\text{OIV}], [\text{NeV}]\)
- Finding dusty AGNs to \(z \sim 4\)
Summary

Multi UV line analysis for HzRGs (z~3)
- Diagnostics without assumptions on major gas parameters
- $U_{\text{NLR}}$ does not depend on $L_{\text{AGN}} \rightarrow$ consistent to Kaspi’s relation
- Solar or super-solar metallicity $\rightarrow$ no strong redshift evolution

Rest-optical diagnostics for high-z luminous quasars (z~3)
- [OII]-detected & undetected quasars: two populations?
- [OII]-detected quasars show similar flux ratios to low-z quasars
- [OII]-undetected quasars: $\sim1$ dex higher $n_{\text{NLR}}$ than low-z quasars
- Such dense gas clouds are distributed at the scale of their hosts

Future prospects
- Subaru/PFS systematic spectroscopy of NLRs in high-z AGNs
- Targets will be from HSC-SSP and HSC-eROSITA collaboration
- Where are metal-poor AGNs? $\rightarrow$ Future surveys with SPICA