WERGS: Wide and Deep Exploration of Radio Galaxies with Subaru HSC

Takuji Yamashita (NAOJ) and the WERGS collaboration
Radio Galaxies (RGs)

“Active galactic nuclei (AGNs)” luminous in radio wavelength

Radio emission
- Powerful radio jets/lobe and core
- Synchrotron driven by a SMBH

Definition
- \( \frac{L_{5\text{GHz}}}{L_B} > 10 \) [Kellermann+1989]
- \( L_{1.4\text{GHz}} > 10^{24} \text{ W/Hz} \) [Tadhunter 2016]

- Important population in evolution/formation of AGNs/galaxies
- Good target to study the high-z universe
  - they are very bright in radio
  - but generally faint in optical/UV

Hercules A radio galaxy (HST&JVLA)
Radio Galaxies

Important population in evolution/formation of AGNs/galaxies

Evolution of radio AGNs

- Powerful radio jets can regulate star formation in host galaxies and surrounding galaxies
- “radio mode” feedback is demanded to reproduce the cut-off at the bright end of galaxy LF.

Evolution of hosts of radio galaxies

- Local radio galaxies are passive and massive host galaxies, and their SMBHs show low accretion rates, while high-z radio galaxies show high star formation.
- What is the evolution linking radio galaxies in low-z and high-z?

Protoclusters

- Radio galaxies are a valuable beacon for protoclusters, because radio galaxies are often found in overdense regions in universe.
- Radio galaxies, however, do not always reside at overdensities.
Previous Radio galaxy samples

**Classical samples**
- e.g., 3CR, 4C, PKS, 2Jy, ...
- low-z & high-z
- Highest radio luminosities (Jy-levels)

**Wide-field samples**
- SDSS & VLA FIRST
  - e.g., Best & Heckman 2012
  - Wide fields: >~ 1,000 deg$^2$
  - Optically-bright (i<21) & low-z RGs (z<0.5)

**Deep-survey samples**
- e.g., VLA-COSMOS, SXDF
  - e.g., Smolcic et al. 2017
  - Deep imaging (i~<26)
  - Less numbers of rare objects
  - Small area (~1 deg$^2$)

Missing piece…
→ **Wide field & Deep survey**
Subaru Hyper Suprime-Cam Survey (HSC)

- Wide & Deep imaging survey
  - 5 BBs & 4 NBs
  - 3 survey layers
  - 1400 deg$^2$ & $r \sim 26$ in the Wide layer
  - started in 2014; 5-6 yrs project

<table>
<thead>
<tr>
<th>Layer</th>
<th>Area (deg$^2$)</th>
<th>Filters &amp; Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>1400</td>
<td>grizy($r \sim 26$)</td>
</tr>
<tr>
<td>Deep</td>
<td>27</td>
<td>grizy+4NBs ($r \sim 27$)</td>
</tr>
<tr>
<td>Ultradeep</td>
<td>3.5</td>
<td>grizy+4NBs ($r \sim 28$)</td>
</tr>
</tbody>
</table>
**Subaru Hyper-Suprime Cam Survey**

- **Wide & Deep imaging survey**
  - 5 BBs & 4 NBs
  - 3 survey layers
  - 1400 deg² & r~26 in the Wide layer
  - started in 2014; 5-6 yrs project

Wide & Deep imaging

Radio galaxies

at new parameter spaces

(many high-z RGs & rare objects)
Wide and Deep Exploration of Radio Galaxies with Subaru HSC

**Exploration of high-z or optically faint radio galaxies with Subaru HSC in order to tackle the issues on the galaxy/AGN evolution.**

**Members:**
Y. Yamashita (PI)

**Publication**
- Paper II: “Multiwavelength data & SED fitting” (Toba et a. 2019)
- Paper III: “Discovery of z=4.7 High-z Radio Galaxy” (Yamashita et al. 2019 submitted)

**Follow-up**

- JVLA
- Optical Spec.
- X-ray (eROSITA)
- Environments
# HSC-FIRST photo-z sample

## HSC-SSP

- Wide & Ultra-Deep COSMOS layers (2016 Release version)
- S/N (r,i,z) > 5

<table>
<thead>
<tr>
<th></th>
<th>Wide</th>
<th>Ultra-Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limiting mag i [mag]</td>
<td>26.4</td>
<td>27.0</td>
</tr>
<tr>
<td>Area [deg²]</td>
<td>154</td>
<td>2</td>
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</tbody>
</table>

## VLA FIRST 1.4GHz survey

- 1.4 GHz (20 cm) continuum imaging
- Area = 10,575 deg²; ~ SDSS
- Detection limit = 1 mJy
  - relatively shallow → detect radio-AGNs but not detect distant SF galaxies (z > 0.5)
- Resolution = 5″, Accuracy < 0.5″

## Cross-match

- Between FIRST and HSC-SSP (i-band) with a search radius = 1″.0
- Focus on matching to radio-core; complex morphology radio sources is minor (10%)
- **3579 matches in Wide; 63 matches in UD-COSMOS**

Yamashita+18
Photo-z of the HSC-FIRST samples

- Mizuki SED template fitting (Tanaka 2015)
- 2,713 RGs (Wide) and 49 RGs (UD) have secure photo-z
- Almost all the sources have photo-z of 0.2 - 1.5
- Optically faint (HSC-level) RGs are located at $z \gtrsim 1$

Yamashita+18
Multiwavelength SED fitting

- u - radio SED fitting w/ CIGALE (Toba+19)
- Decomposition of stellar, SF, AGN, and synchrotron

Toba, TY +19
SED fitting results

- Optically faint (higher-z) RGs have
  - higher SFR
  - larger extinction
  - some have less-massive

- Different picture:
  
  📇 $z \sim 1$ RGs have dusty star-forming host galaxies, while $z \sim 0$ RGs are passive and dust-poor.

Toba, TY +19
- Optically faint (higher-z) RGs have:
  - higher SFR
  - larger extinction
  - some have less-massive

- Different picture: z~1 RGs have dusty star-forming host galaxies, while z~0 RGs are passive and dust-poor.

Toba, TY +19
z > 4 High-z Radio galaxies

Evolution of radio galaxies
• Number density (ND) moderately increases up to \( z = 1 - 2 \)
• Abruptly decline at \( z \sim 2 - 3 \)
• At \( z > 3 \), ND is not well constrained due to a dearth of HzRG samples

\( z > 4 \) HzRGs
• Only 13 HzRGs discovered to date.
• All known \( z > 4 \) RGs were found with an ultra-steep spectrum technique (USS), except for one HzRG.
• Empirical relation of \( z - \alpha \)
  • \( \alpha < -1.3 \) \((S_\nu \propto \nu^\alpha)\)
• Non-USS HzRGs reported

Dunlop & Peacock 90; Rigby+15

325MHz-1.4GHz spectral index vs. redshift
(De Breuck et al. 2000)
Our Approach: Lyman Break Radio Galaxies

Apply “Lyman break technique” to HzRG search

- HSC Survey enables us to use Lyman break technique for HzRGs
  - The best way for high-z surveys (e.g., Ono+18; Matsuoka+18)
  - Using the HSC 5 broad-band filters, \( z = 3.5 - 7.0 \) HzRGs will be found
- Not relying on USS
  - no bias of radio SED
**r-dropout HzRGs (z~5)**

### 1. Dropouts
- Lyman break for FIRST radio sources
  - *riz* color selection for z ~ 5 radio sources
    (ref. the COLDRUSH project, Ono et al. 2018)
  - 16 *r*-band dropouts (z ~ 5 candidates) in the HSC-SSP region.

### 2. Follow-up spectroscopy
- Gemini-FT/GMOS spectroscopy in Feb 2018
  - for a z~5 candidate
    - z_AB = 23.5 mag
    - 2 hours exposures
Redshift

- Asymmetric line profile & r-dropout $\rightarrow$ Lyα line
- **Redshift: $z = 4.72$**
  - the fourth-most distant known RG, following $z=5.7$ (Saxena+18), $z=5.2$ (van Breugel+99), and $z=4.9$ (Jarvis+09)

Lyα properties

- $\text{EW}_0(\text{Ly}\alpha) = 9.1$ Å
  - The small EW might mean a dusty & chemically-evolved system (Ando-relation)
- $\text{FWHM}_{\text{obs}} = 660$ km/s

Yamashita+19 submitted
The host galaxy

- \( \log \frac{M_*}{M_\odot} = 11.4 \) at the cosmic age of 1.2 Gyr
- The \( K_s \) magnitude is consistent with the \( K - z \) relation for RGs
- The massive end of MF of \( z \sim 5 \) Lyman break galaxies (e.g., Yabe et al. 2009)
- The stellar mass had been Rapidly built up
- The SF should stop shortly and it could evolve to a giant elliptical galaxy

SED fitting (CIGALE code)

Yamashita+19 submitted

- HSC grizy
- VIKING ZYJHKs
- WISE W1W2
Not Ultra-Steep Spectrum

Radio spectral index

- \( \alpha_{(325\text{MHz}-1.4\text{GHz})} = -1.1 \)
- \( \alpha_{(150\text{MHz}-1.4\text{GHz})} = -0.97 \)

\( \Rightarrow \) Non USS

\( \star \) USS definition: \( \alpha < -1.3 \)

(De Breuck et al. 2000, Saxena et al. 2018)

- This HzRG is never discovered by USS
- WERGS provides a complementary sample to the USS selection sample

Yamashita+19 submitted
Summary

- **WERGS photo-z sample**:  
  - ~3600 RGs from HSC-FIRST cross-match (Yamashita+18)  
  - Identified z>1 RGs at the optically faint regime

- **Multi-wavelength SED fitting of photo-z sample**:  
  - z~1 RGs have higher SFR and larger extinction than local RGs (Toba+19)  
  - WERGS photo-z sample provides the different picture of RGs from local knowledge.

- **Lyman break radio galaxy**:  
  - z = 4.7 HzRG found by WERGS  
  - Massive (logM*/Msun=11.4) and non-USS (α = -1)  
  - Demonstrate the power of Subaru HSC for HzRG survey