The GLEAMing of the first supermassive black holes: peaked-spectrum sources at high redshift

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Why study HzRGs?

- Vital probes of massive galaxy formation and evolution (review by Miley & De Breuck 2008).
- Extreme SMBH and host galaxy growth – e.g. QSO J0313-1806 @ $z = 7.64$; $1.6 \times 10^9 \, M_\odot$ BH, 670 Myr after the Big Bang (Wang et al. 2021).

Rocca-Volmerange et al. 2004

Greyscale: Hubble ACS
Red: VLA 8 GHz
Blue: VLT Lyα

Miley et al. 2006
‘Spiderweb Galaxy’ @ $z = 2.156$
The importance of low-frequency radio observations

- HzRGs traditionally found via USS selection in the radio ($S_{\nu} \propto \nu^\alpha$ where $\alpha \leq -1.3$ (or -1.0); e.g. De Breuck et al. 2000).


- Our HzRG project: uses radio spectral steepness and curvature from MWA/GLEAM (Wayth et al. 2015). Redshift from ALMA molecular lines.

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$S_{147.5} = 170$ mJy; linear size = 3.5 kpc

Drouart et al. 2020

Saxena et al. 2018
Discovery of GLEAM J0856: a HzRG at $z = 5.55$

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Paper on our pilot sample now published (Drouart et al. 2020, PASA, 37, e026)
GLEAM J0917 – ALMA and JVLA observations

- Pilot study suggested GLEAM J0917 could be at $z = 10.15$.

- ALMA DDT re-observation of CO lines (PI Drouart; $2 \times 40$ min).

- JVLA DDT Q-band: CO(4-3) and [CI(1-0)] if $z = 10.15$ (5 hr on source; PI Drouart.)

- Both follow-up observing campaigns: no molecular lines detected.
GLEAM J0917 broadband radio–IR SED

Drouart et al. 2021, submitted
GLEAM J0917 – an enigmatic source


- Very radio-loud object. Molecular gas-poor system; also lack of dust ($< 10^7 \, M_\odot$).

- A peculiar object if $z < 5$.

- More likely solution: $z > 5$.

- *HST* imaging and grism observations taken; Cycle 28 (PI Seymour).

- First *HST* imaging observation (F105W) also consistent with a very high-$z$ source. *Stay tuned: grism observations currently being analysed.*

Seymour et al. in prep.

Drouart et al. 2021, submitted
GLEAM J0917 – an enigmatic source

Polarimetric properties:

Not polarised at our observing frequencies below 10 GHz.

MWA interplanetary scintillation (IPS) observations (Morgan, Chhetri et al.):

Half of the flux density at 162 MHz is on a scale ≤ 0.5 arcsec (≤ 3.1 kpc for z ≥ 5).

Upcoming Long Baseline Array VLBI 2.3-GHz observations in July (PI Broderick):

Up to 200x improvement in angular resolution cf. our ALMA 100-GHz data.

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LOFAR low-band observations

- Constraining the low-frequency spectra of GLEAM J0856 and J0917.
- LOFAR project LC14_016 (PI Broderick).

- 7 × 3-hr observations from 2020 June – September.
- Frequency range 34–66 MHz (i.e. lower than GLEAM).

- Using LBA direction-dependent pipeline (de Gasperin et al.) on CSIRO HPC cluster Pearcey.

In collaboration with George Heald (CASS) and Francesco de Gasperin (Hamburg). Thanks also to Nadia Biava (Bologna).
LOFAR low-band initial images

Very preliminary results!

Broderick et al. in prep.

LOFAR LBA equatorial imaging – both sources clearly detected!

Run 7; 2020 September 13
50 MHz; 32 MHz bandwidth
Direction-independent cal. + one round direction-dependent cal.
15 arcsec resolution
Noise level ~5 mJy beam$^{-1}$

- LOFAR LBA equatorial imaging – both sources clearly detected!

J0856

$S_{50} \approx 2$ Jy
$\alpha(50–76) \approx -0.8 \pm 0.3$

J0917

$S_{50} \approx 570$ mJy
$\alpha(50–76) \approx 0.4 \pm 0.5$
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Broderick et al. in prep.
GLEAM J0856 radio spectrum

- Image 8 × 4-MHz channels across the LOFAR bandwidth (36, 40, …, 64 MHz).
- Full direction-dependent calibration still to be applied.
- Other runs to be processed as well.
- Noise level per 4-MHz channel: ~10–20 mJy beam⁻¹ for one run!

An interesting test case for low-frequency flux scale accuracy (LOFAR+GLEAM+VLSSr)?

GLEAM, VLSSr: Baars et al. 1977
LOFAR: Scaife & Heald 2012

Corrections (~0.85×) applied to LOFAR measurements to line up low-frequency flux scales to first order.

Evidence of a spectral turnover at ≲ 30 MHz
(i.e. rest frame ≲ 200 MHz)

Spectral fitting: MRMOOSE (Drouart & Falkendal 2018)
- Turnover frequency $\sim 30–40$ MHz (rest frame $\sim 200–260$ MHz).
- Peak flux density $\sim 1.7–2$ Jy, $\alpha_{\text{thin}}$ ($\leq 1.4$ GHz) $\sim -1$.
- $B_{\text{equip}} \sim 0.9$ mG (Duffy & Blundell 2012 framework; curved radio spectra).

Using standard model formulae with an upper frequency cutoff of 1.4 GHz for the fitting (higher-frequency spectral steepening).

Cannot distinguish between SSA and FFA with current data.

Equatorial LOFAR imaging for $\nu < 30$ MHz? Potential LOFAR 12–31 MHz northern sky survey; test observations have started (van Weeren et al.).
Expanding our pilot study

- GLEAM Year 1 catalogue (GLEAM Exgal; Hurley-Walker et al. 2017), and GLEAM Year 1 + 2 where available (GLEAM SGP; Franzen et al. 2021). 72-231 MHz.
- ESO VISTA VIKING NIR survey (Edge et al. 2013). 2.15 μm (Ks-band).
- Sample defined over ~1200 deg² (~20 × GAMA-09 pilot study).

- Goal: build a sample of HzRGs within the Epoch of Reionisation (z > 6.5).

http://www.mwatelescope.org/multimedia/images/  
https://www.eso.org/public/images/eso0704b/
Sample selection criteria

Key considerations:

- Radio flux densities $S_{151} > 40 \text{ mJy}$

- Radio morphology $\text{LAS} \leq 5 \text{ arcsec}$ (see e.g. Blundell & Rawlings 1999; Saxena et al. 2017)

- Radio spectrum
  - Steepness: $\alpha \leq -0.7$
  - Curvature: $\beta \leq -0.3\alpha - 0.51$

- Near-infrared magnitude $K_s > 21.2 \ (5\sigma; \ AB)$ (see e.g. Ker et al. 2012)
New HzRG candidates

- VIKING $K_s$ overlaid with 1.4-GHz FIRST contours (Becker et al. 1995).
- Also used 3-GHz VLASS (Lacy et al. 2020), 890-MHz RACS (McConnell et al. 2020) and 5.5/9-GHz ATCA data (our observing campaign in 2020 May + December).

- New sample: 55 sources. ~70% with LAS $\leq$ 2 arcsec ($\leq$ 13 kpc @ $z \geq$ 5).
- Sample definition paper: Broderick et al. in prep.
Broadband radio spectra

![Graph showing broadband radio spectra with frequency on the x-axis and flux in Jy on the y-axis. The graph includes data from GLEAM, TGSS, NVSS, VLASS, and ATCA.](image)
**Broadband radio spectra**

- SED fitting with MRMOOSE (Drouart & Falkendal 2018).
- Spectral modelling: energy loss mechanisms; information about ambient environments; further investigation of HzRG selection procedure (e.g. Morabito & Harwood 2018).
- Spectral breaks: determine jet ages/powers (e.g. Turner et al. 2018).

\[ \alpha_{\text{low}} = -1.42, \quad \alpha_{\text{high}} = -2.44, \quad \nu_{\text{break}} = 1.38 \text{ GHz} \]

\[ \alpha_{\text{low}} = -0.66, \quad \alpha_{\text{high}} = -1.45, \quad \nu_{\text{break}} = 2.40 \text{ GHz} \]

Broderick et al. in prep.
Next observing campaigns

VLT HAWK-I deep $K_s$-band imaging

ALMA imaging + spectroscopy.

Proposals submitted for recent ESO and ALMA deadlines
Conclusions and future work

- Discovery of GLEAM J0856 @ $z = 5.55$. Second-most distant radio galaxy currently known.

- Solving the mystery of the enigmatic source GLEAM J0917 – stay tuned!

- LOFAR LBA detections of GLEAM J0856/J0917 down to 36 MHz. Tentative detection of turnover at ~30–40 MHz for J0856. Ongoing work to constrain low-frequency spectra of both J0856/J0917.


Find $z > 6.5$ powerful radio galaxies: exciting EoR science!