Resolving the Radio-Loudest Quasar known to date at z~6

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Introduction: High-z QSOs

- At \( z \gtrsim 6 \) we are probing the era near the end of the Cosmic Reionization.
- Various surveys (e.g., SDSS, SHELLQs, Pan-STARRS1) found large samples of QSOs out to \( z \sim 6 \) and beyond.
- To date, more than 150 quasars at \( z \gtrsim 6 \) have been identified.
- Only two at \( z > 7 \); the highest-z QSO known-to-date is at \( z = 7.54 \).
RLQs

• Luminous radio quasars and radio galaxies are likely to reside in more massive galaxies and to harbor more massive central black holes.

• Roughly 10%-20% of all quasars are radio-loud (R>10)

• Evolution of the Radio Loud Fraction (RLF) with z
  – RLF of quasars decreases with increasing redshift and decreasing optical luminosity (0 < z ≤ 5: Jiang et al. 2007).

• At high-z, may allow to probe the formation of radio jets in the first quasars.
Radio-loud QSOs @ \( z \sim 6 \)

A total of seven known RLQs at \( z > 5.8 \), five imaged with VLBI

- J1609+3041 \( z=6.14 \) No VLBI
- J2053+0047 \( z=5.92 \) No VLBI
- J0836+0054 \( z=5.81 \) Frey et al. 2005
- J2228+0110 \( z=5.95 \) Cao et al. 2014
- J1429+5447 \( z=6.18 \) Frey et al. 2011
- J1427+3312 \( z=6.12 \) Frey et al. 2008, Momjian et al. 2008
- P352.15 \( z=5.84 \) Momjian et al. 2018
VLBI: RLQ at z~6

- \( z = 5.81 \)
- Peak: 333 \( \mu \text{Jy/beam} \)
- A few mas size \( \Rightarrow T_b \sim 10^6 \text{ K} \)

- \( z = 5.95 \)
- Peak: 267 \( \mu \text{Jy/beam} \)
- A few mas size \( \Rightarrow T_b > 10^8 \text{ K} \)
VLBI: RLQ at $z \sim 6$

- $z=6.18$
- Peak: 2.3 mJy/b at 1.6 GHz, 0.67 mJy/b at 5 GHz.
- A few mas size $\Rightarrow T_b > 10^9$ K
- The entire emission region is confined to within 10 pc at 5 GHz

Frey et al. 2011
The $z=6.12$ QSO J1424+3312

- $T_b \sim 10^7$ to $10^8$ K.
- The flux density ratio is $\sim 3:1$, separated by 31 mas; 174 pc.
- $\alpha(5-1.4) = -0.67$

Frey et al. 2008

Momjian et al. 2008
Powerful RLQs near $z \sim 6$?

• There seems to have been a lack of powerful radio quasars at $z > 5.5$
  – $S_{1.4} > 10$ mJy ($L_{v,1.4\text{GHz}} > 10^{27}$ W/Hz)

• This changed in September 2017 with the discovery of
  PSO J352.4034−15.3373 ($P352-15$)
The Discovery of P352-15

- $z \sim 6$ quasar candidate from PanSTARRS1
- Confirmed as a quasar on Sep. 26, 2017, using Magellan Clay telescope in Las Campanas Observatory.
- $z = 5.84 \pm 0.02$
- Also, a tentative detection of an associated absorber at $z=5.8213$ (dense local environment, or outflow)

Bañados et al. 2018
Matching with Existing Radio Surveys

- NVSS (1.4 GHz)  
  \[14.9 \pm 0.7 \text{ mJy}\]
- GLEAM WIDE (200 MHz)  
  \[87.8 \pm 6.9 \text{ mJy}\]
- TGSS peak (150 MHz)  
  \[110.6 \pm 13.8 \text{ mJy}\]
- TGSS total (150 MHz)  
  \[163.1 \pm 20.7 \text{ mJy}\]
VLA High Angular Resolution Follow-up: The Confirmation

- **B-configuration**
- **S-band (2-4 GHz).**
- **Jan. 13, 2018 (B-config)**
- **Resolution: 2.6” x 1.4”**
- **Unresolved (≤ 0.5”)**
- **$S_{3\text{GHz}} = 8.2 \pm 0.25$**

Bañados et al. 2018
• $L_{\nu,1.4} = 4.5 - 6.3 \times 10^{27}$ W/Hz
• The most powerful radio source at $z \sim 6$
Radio Loudness

- $R \gtrsim 1000$
- One order of magnitude more radio loud than any other source at $z > 5.5$

Bañados et al. 2018
VLBA Follow-up

- January 23, 2018
- L-band (1.5 GHz)
- Dual pol, 256 MHz bandwidth (2 Gbps recording)
- Time: 2 hrs
- Phase referenced (calibrator 0.7 degrees away)
Resolving the Radio Emission

- Beam size 23.9 x 11.3 mas (139 x 66 pc at z=5.84)
- RMS noise 67 µJy/beam
VLBA Results

• Three distinct emission regions.
• Total extent: 1.62 kpc (0.28")
• Total flux density: $6.57 \pm 0.38$ mJy; ~50 % recovered.
• $T_b: 1 \times 10^7$ to $> 13 \times 10^7$ K

$E \sim 1.2$ mJy
$C1+C2 \sim 1.5$ mJy
$W1+W2 \sim 3.9$ mJy
Two Scenarios

- Two possible interpretations with the existing data:
  1. A core with a one sided jet
  2. A classic but compact FRII source
- Need multi-frequency VLBI data to identify a core
A Core with a One-sided Jet

- E is the core, C and W are part of the jet structure.

$\mu_{\text{max}} \sim 0.2 \text{ mas/yr}$

Frey et al. 2015
A Compact FR II Source

- The core is in C, and E and W are the lobes/hotspots.
- A CSO/MSO
- Assuming a typical advance speed of 0.2c for CSOs
  - Age of source: $10^4$ years
  - Separation between hotspots $\sim 20 \mu$as/yr
Open Questions and Future Observations

- Is it a core+jet or a CSO/MSO?
  - VLBA multi frequency observations
- Associated HI absorption if CSO/MSO
  - GMRT (DDT time approved, also assess the system)
- Probe the neutral IGM in HI absorption (21cm forest)
  - ~10% neutral fraction at z~6 (Greig and Mesinger 2017)
  - GMRT: ~100 hr needed (1% optical depth, 10 km/s)
Open Questions and Future Observations

- X-ray properties
  - Chandra

- Estimate the mass of the SMBH, accretion rate, confirm the associated absorber (may indicate dense environment or strong outflow)
  - Gemini

- Dust and [CII] emission; search for (anti-) correlation between radio and mm dust emission.
  - ALMA
Summary

• Recently discovered the radio-loudest quasar at $z \sim 6$.
• A resolved radio source with a $1.62$ kpc linear extent.
• May be
  – Core with one-sided jet
    • measure the proper motion
  – CSO/MSO $\rightarrow$ age of source $\sim 10^4$ yr
• Multiple follow-up observations planned
  – From X-ray, to searching for redshifted HI
• The new discoveries of quasars at $z \gtrsim 6$ and follow-up studies (including VLBI) are key to understand and constraint the feedback processes in the earliest galaxies.