Multi-wavelength Observations
High Redshift Radio Galaxies

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Overview

- Why study High Redshift Radio Galaxies (HzRGs)?
- Searches for HzRGs: the Ultra Steep Spectrum technique.
- Dust and CO in high redshift radio galaxies (HzRGs).
- Dusty starbursts in a $z=4.1$ proto-cluster?
- Spectropolarimetry of HzRGs.
- Other projects.
What are HzRGs?

- Galaxies with an AGN type II (narrow emission lines).
- Powerful radio sources with FR-II morphology (edge brightened lobes).

Radio map of Cygnus A at z~0

*Carilli and Barthel, A&A Reviews, 7, 1*
Why study HzRGs?

- Most luminous and massive galaxies at high z.
- Tracers of (proto-)clusters.
- Radio selection is insensitive to dust properties.
- Clear view of the host galaxy (unlike quasars).
- Can be studied in detail from radio to X-ray.
- Can be studied from $z=0$ to $z=5$. 
The Hubble K-z diagram of radio and optically selected galaxies

- K band traces stars.
- Radio galaxies follow the 'K-z relation'.
- Radio galaxies are more luminous ⇒ more massive.
- Explanation: powerful radio source ⇒ $10^9 \, M_\odot$ black hole ⇒ massive bulge.

Distribution of $z>2$ radio galaxies on the sky
The Ultra Steep Spectrum (USS) search technique

Radio spectrum of Cygnus A

\[ z - \alpha \text{ correlation in unbiased samples} \]

Radio spectrum is concave \( \Rightarrow \) Steeper part of spectrum gets redshifted to observed frequencies
All-sky USS samples

Sample definitions:
- WENSS-NVSS (WN): $\alpha<-1.30$, $S_{1400}>10$ mJy
- Texas-NVSS (TN): $\alpha<-1.30$, $S_{1400}>10$ mJy
- MRC-PMN (MP): $\alpha<-1.20$, $S_{408}>700$ mJy
- SUMSS-NVSS: $\alpha<-1.30$, $S_{843}>25$ mJy

Radio surveys

Sky distribution of the 669 USS sources

De Breuck et al. 2000, A&ASup, 143, 303
The Most Distant Radio Galaxy

**Identification:**
Keck NIRC K-band.
VLA 14.9 Ghz.
K(2")=21.3
α = -1.63

**Redshift determination:**
3 hour Keck LRIS spectrum.
Single emission line, identified as Lyα by exclusion of confirming lines if it were [OII] λ3727, [OIII] λ5007, or Hα.

TN J0924-2201, z=5.19

SCUBA surveys of HzRGs

- Radio selection is unbiased towards dust properties.
- SCUBA 850 µm photometry of 70 radio galaxies with 0.7<z<5.2.
- 850 µm luminosity increases with z.
- Higher star formation rate at z>3?

CO and dust High z radio galaxies

- The dust in HzRG can be heated by massive starbursts or directly by the AGN.
- Two dusty z~3.5 radio galaxies also show CO emission, indicating a large reservoir of gas providing fuel for the starburst.

Questions:
- Is there a difference between quasars and radio galaxies?
IRAM Plateau de Bure observations of HzRGs

Keck K-band with integrated CO (4-3) contours

B3 J2330+3927, z=3.087

TN J0121+1321, z=3.516
The CO spectrum of B3 J2330+3927

- PdBI 3mm spectrum extracted at object a shows the CO (4-3) line + faint continuum.
- CO line is offset by 500 km/s wrt HeII λ 1640 emission line. Such offsets are also seen in quasars and submm-selected galaxies.

De Breuck et al. 2003, A&A 401, 911
Lyα and CO velocity profiles


- The CO emission is coincident in velocity with the strongest HI absorber in Lyα.
  \[ \Rightarrow \text{physical connection between the molecular and neutral gas.} \]

- We have searched for HI 21cm absorption from this absorber with WSRT, but did not detect absorption down to \( \tau < 1.3\% (3\sigma) \).
  [More sensitive GMRT observations obtained on 21 Oct 2003].
In more than half of the HzRGs, the CO emission is very close in velocity with the strongest HI absorber in Lyα.

Dotted line: HeII λ 1640 redshift
Horizontal bars: full CO width.
Mass Estimates

- Assuming a conversion factor between CO and H$_2$ yields M(H$_2$).
- Assuming an average shape of the thermal dust spectrum (which fits well our SED), we can estimate the total dust mass.
- Assuming case B recombination at T=10$^4$ K, a volume and filling factor, the Ly$\alpha$ luminosity yields M(HII).
- The Voigt absorption profile in Ly$\alpha$ provides an absorbing column density; assuming a size, this yields M(HI).
- The upper limit on the HI 21cm absorption provides a similar estimate, by assuming a spin temperature and profile width.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass estimate $M_\odot$</th>
<th>Determined from</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>$7 \times 10^{10}$</td>
<td>CO (4 – 3) line</td>
</tr>
<tr>
<td>Dust</td>
<td>$9 \times 10^{7}$</td>
<td>850$\mu$m continuum</td>
</tr>
<tr>
<td>HII</td>
<td>$2.5 \times 10^{8}$</td>
<td>Ly-(\alpha) emission</td>
</tr>
<tr>
<td>HI</td>
<td>$2 \times 10^{7}$</td>
<td>Ly-(\alpha) absorption</td>
</tr>
<tr>
<td>HI</td>
<td>$&lt;2 \times 10^{8}$</td>
<td>HI 21 cm absorption</td>
</tr>
</tbody>
</table>
HzRGs as tracers of (proto-)clusters

TN J1338-1942, z=4.1

VLT large program:
2. Selection based on excess narrow-band.

→ Confirmed companions: 14 to 28 around four radio galaxies at z=2 to z=4.1.

\[ M = \rho (1+\delta_m) V \sim 10^{15} M_\odot \]

Multi-λ observations of the proto-cluster around a z=4.1 radio galaxy

The deep optical VLT images may not detect dust-obscured companion objects.

We have obtained a 1.2mm map using MAMBO at the IRAM 30m.

Complemented by a 12h VLA 1.4 GHz map for R-band identifications.

None of the 15 spectroscopically confirmed Lyα companions are detected at 1.2mm.

We find 3 bright 1.2mm sources, while <1 are expected.
Sky distribution: mm sources coinciding with void of Ly\(\alpha\) emitters?
Photometric Redshift Determination

- Correlation between thermal radio (1.4 GHz) and far-IR provides a redshift estimate \((e.g. \text{Yun} \& \text{Carilli} 2002)\).
- Combination with 850 and 450 µm photometry (SCUBA/JCMT) → dust SED fitting.
Spectropolarimetry of HzRGs

- Provides a means to determine the contribution of scattered quasar light to the UV continuum.
- Specpol of $z \approx 2.5$ radio galaxies find $P=5\text{-}20\%$. (Vernet et al 2001)
- We have observed 4 new radio galaxies at $3<z<4.1$, and find $P<7\%$.
- Two unpolarized $z \approx 3.8$ radio galaxies show stellar absorption lines $\Rightarrow$ massive starbursts.
Starbursts in HzRGs

- Unpolarized UV continuum + strong submm emission $\Rightarrow$ starbursts heating the dust.

- Highly polarized UV continuum $\Rightarrow$ more scattered quasar contribution, but less massive starburst.

CIII $\lambda$1428 photospheric absorption line in TNJ2007-1316 at $z=3.84$. 
Other projects

- CO and spatially resolved dust in radio galaxy 4C41.17 at z=3.8.
- Search for HI 21cm absorption in HzRGs using GMRT.
- Spectropolarimetry of BALQSOs.