CO(1-0) survey of high-z radio galaxies with the Australia Telescope Compact Array

Bjorn Emonts  (CSIRO Astronomy & Space Science/ATNF)
This talk

• **Australia Telescope Compact Array upgrade**
  Excellent southern telescope for high-z mm studies

• **CO(1-0) survey of high-z radio galaxies (HzRGs) with ATCA**
  MRC 0152-209: strongest CO(1-0) detection in HzRG to date

**Team:**
- Minnie Mao *(U. Tasmania)*
- Ilana Feain *(CASS)*
- Ray Norris *(CASS)*
- George Miley *(Leiden Obs.)*
- Montse Villar-Martin *(IAA Granada)*
- Huub Rottgering *(Leiden Obs.)*
- C. Carilli *(NRAO)*
- Ron Ekers *(CASS)*
- Elaine Sadler *(U. Sydney)*

High-z Radio Galaxies (HzRG)

- Most massive galaxies in Early Universe
  - Central proto-cluster galaxies (e.g. Venemans et al. 2007)
    → ancestors of local rich cluster ellipticals
  - Clumpy optical morphology (merging systems) (Pentericci et al. 2001);
  - Radio jets vigorously interact with ISM (Humphrey et al. 2006) + alignments jets with UV/optical and CO (Chambers et al. 1987; McCarthy et al. 1978; Klamer et al. 2004).

- Among best studied high-z objects
  - Strong radio continuum beacon for tracing faint host galaxy/proto-cluster;
  - Optical quasar-core generally shielded by torus

4C41.17 (z = 3.8) (Reuland et al. 2003)

VLA radio on Keck Lyα
HST Image, WFPC2 (7000A)

To fully understand HzRGs: Holistic approach!
Molecular gas in HzRG

• Molecular gas: raw ingredient for star formation
  • $\text{H}_2$ virtually invisible -- $^{12}\text{CO}$ strong tracer (rotational transitions):
    $\text{CO}(1-0)$ [115 GHz], $\text{CO}(2-1)$ [230 GHz], $\text{CO}(3-2)$ [345 GHz], $\text{CO}(4-3)$ [460 GHz], etc.
  • 1991: First observations of CO at $z > 2$ (Brown & Vanden Bout 1991)

• CO as tracer for molecular gas in HzRGs:
  • First (single-dish) surveys failed to detect CO (Evans et al 1996, van Ojik et al 1997)
  • CO found on scales of tens of kpc (e.g. Papadopoulos et al. 2000), in giant Ly$\alpha$ halos (Nesvadba 2009) and aligned with radio jets (Klamer et al 2004)

4C41.17 ($z = 3.8$)
Reuland et al. (2003); Carilli et al (1997)

VLA radio on Keck Lya
HST Image, WFPC2 (7000A)

De Breuck et al. (2005)
CO studies of HzRG

- Major limitations plagued comprehensive studies of high-z CO:
  - **Limited bandwidth**, often not wider than CO signal or z-accuracy;
  - **Limited collecting area/sensitivity**, requiring long integration times (pre-selection on IR or submm flux);
  - **High observing frequencies** (>100 GHz) of mm observatories:
    Only target higher-order CO($J,J-1$) transition at high-z.
    - **High-order transitions**: dense and thermally excited gas in starburst/AGN region;
    - **Low-order transitions**: less dense, widespread, sub-thermally excited gas;

*Ground-transition CO(1-0): most robust tracer for molecular gas at high-z (incl low-density, widespread and sub-thermally excited component) – crucial for tracing the overall molecular gas content!*
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  - High-order transitions: dense and thermally excited gas in starburst/AGN region;
  - Low-order transitions: less dense/widespread, sub-thermally excited gas;

  \[ \rightarrow \text{large reservoirs of molecular gas missed by observations of high-order transitions} \]

- Ground-transition CO(1-0): most robust tracer for molecular gas at high-z (incl. low-density, widespread and sub-thermally excited component) – crucial for tracing the overall molecular gas content!
CO studies of HzRG

• Major limitations plagued comprehensive studies of high-z CO:
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Credit: J. Ott (NRAO) (Walter & Carilli 2008)
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Credit: J. Ott (Walter & Carilli 2008)
Australia Telescope Compact Array

- upgraded with *Compact Array Broadband Backend (CABB)* in 2009

- 4 (2x2) GHz bandwidth, 1 MHz coarse res., full stokes
- 16 zoom-windows for high-resolution per band
- Observing frequencies 1.1 - 105 GHz
Australia Telescope Compact Array

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- mm observing frequencies
  - 3mm (84-105 GHz)
  - 7mm (30-50 GHz)
  - 15mm (16-25 GHz)

- Hybrid array configurations
  baselines as short as 31m.

Example: at $f_{obf} = 40$ GHz (7mm band) ➔ $\sim 15,000$ km/s per 2 GHz, $\Delta v \sim 7.5$ km/s
Australia Telescope Compact Array

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  - 4 (2x2) GHz bandwidth, 1 MHz coarse res., full stokes
  - mm observing frequencies
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  - Hybrid array configurations
    - baselines as short as 31m.

- EVLA 27 vs ATCA 5/6 dishes;
  - ATCA H75: 15 baselines <100m
  - EVLA D-array: 41 baselines <100m
    (12% of all baselines)
  - EVLA ‘E-array’

- EVLA mm-observations only down to dec ~ -25 deg

Similar for EVLA/WIDAR in the northern hemisphere
CO(1-0) survey of HzRG with ATCA/CABB

- Pilot study: Performance of ATCA/CABB
  - MRC 2104-242 ($z = 2.5$); $f_{\text{obs}} = 33$ GHz (optimum CABB freq.)
  - Upper limit $M_{\text{H}_2} < 2 \times 10^{10} M_{\odot}$ ($\alpha[M_{\text{H}_2}/L_{\text{CO}}] = 0.8$)

$t_{\text{int}} = 19.5\text{h}$

$\sigma_{\text{line}} = 0.45$ mJy/bm/1MHz
$\sigma_{\text{cont}} = 0.29$ $\mu$Jy/bm

CO(1-0) survey of HzRG with ATCA/CABB

• Pilot study: **Performance of ATCA/CABB**
  
  • MRC 0943-242 (z = 2.9) – very edge of 7mm band
  • Tentative off-nuclear detection ($M_{H_2} = 6 \times 10^{10} M_{\text{sun}}$; $\alpha[M_{H_2}/L_{CO}] = 0.8$)

$t_{int} = 19h$

ATCA/CABB: upgraded in 2009

• First high-z CO detection with ATCA/CABB 2 GHz bands:

Coppin et al. (2011):

CO(2-1) in submm-galaxy at z=4.8 !!

$M_{\text{H}_2} = 1.6 \times 10^{10} \, M_{\odot}$ (\(\alpha [M_{\text{H}_2}/L_{\text{CO}}] = 0.8\))
ATCA/CABB: upgraded in 2009

- CO(1-0) @ 3mm in ULIRG IRAS F00183-7111 (z=0.33)

\[ M_{\text{H}_2} \sim 2.4 \times 10^{10} M_{\odot} \]
\[ (\alpha[M_{\text{H}_2}/L_{\text{CO}}]= 0.8) \]
\[ L_{\text{IR}} = 9 \times 10^{12} L_{\odot} \]

Norris et al (in prep)

Norris et al (2011)

VLBI: Compact powerful radio source

Fig. 1: ISO mid-IR (2.5-11.6μm) image of IRAS F00183-7111 from Rigopoulou et al. (1999).
CO(1-0) survey of HzRG with ATCA/CABB

- First systematic survey of CO(1-0) in unbiased sample of HzRGs.

**Sample selection:**
- All HzRGs from MRC catalogue (*unbiased in IR, submm, etc*):
  - observable in ATCA 7mm band (1.5 < z < 3)
  - dec < -10
  - HST imaging & Spitzer data available
  - 14 sources

**Status:**
- 6 sources observed ($t_{int} \sim 15h$ per source)
- 5 sources scheduled in Aug/Sept
CO(1-0) survey of HzRG with ATCA/CABB

- CO(1-0) in z=1.92 radio galaxy MRC 0152-209


$M_{H2} = 6 \times 10^{10} M_\odot$ ($\alpha[M_{H2}/L_{CO}]= 0.8$)

$\Delta v = 400$ km/s

$L_{IR} \leq 7.9 \times 10^{12} L_\odot$; $L_{IR}/L'_{CO} \leq 120$;

SFR $\leq 1362 M_\odot$/yr; $t_{depl} \leq 39$ Myr

Pentericci et al. (2000, 2001)
A CO(1-0) survey of HzRG with ATCA/CABB

- CO(1-0) in z=1.92 radio galaxy MRC 0152-209


\[ M_{H_2} = 6 \times 10^{10} \]
\[ \Delta v = 400 \text{ km/s} \]
\[ L_{IR} \leq 7.9 \times 10^{12} \]
\[ \text{SFR} \leq 1362 \, M_\odot/\text{yr}; \, t_{\text{depl}} \leq 39 \, \text{Myr} \]

MRC 0152-209 likely ULIRG that contains large amounts of molecular gas not yet depleted by star formation or radio-AGN feedback.
CO(1-0) survey of HzRG with ATCA/CABB

- CO(1-0) in z=1.92 radio galaxy MRC 0152-209

Most significant (S/N) CO(1-0) detection in HzRG to date!

- Only two other known CO(1-0) detections in HzRG:
  - TN J0924-2201 – z=5.2 (Klamer et al 2005)
  - 4C60.07 – z=3.8 (Greve et al 2004, Ivison et al 2008)


\[
M_{\text{H}_2} = 6 \times 10^{10} M_\text{s} \quad (\alpha[M_{\text{H}_2}/L_{\text{CO}}] = 0.8)
\]

\[
\Delta v = 400 \text{ km/s}
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Pentericci et al. (2000, 2001)
CO(1-0) survey of HzRG with ATCA/CABB

- CO(1-0) in z=1.92 radio galaxy MRC 0152-209

High resolution CO(1-0) follow-up with ATCA + EVLA

PRELIMINARY RESULTS!

Cold gas reservoir of ~75 kpc! (?)
CO(1-0) peaks off main body/radio jets, in regions devoid of HST emission! (?)

ATCA 1.5km array:
Only ~13% of high-res data!!

Emonts & Mao et al. (in prep)
CO(1-0) survey of HzRG with ATCA/CABB

ALMA Early Science Proposal

CO(6-5) observations dense molecular gas in MRC 0152-209

- Match CO(1-0) observations spatially and kinematically
- CO(6-5)/CO(1-0) composition across host galaxy
- Compare with distinct HST features

ALMA cycle-0 Simulations

CO excitation ladder

Riechers et al (2009)
CO(1-0) survey of HzRG with ATCA/CABB

• First systematic survey of CO(1-0) in unbiased sample of HzRGs.

• **Status (14 sample sources):**
  
  - 6 sources observed  
    \( t_{\text{int}} \approx 15\text{h per source} \)
  
  1 detection
  1 tentative detection

  - 5 sources scheduled in Aug/Sept

<table>
<thead>
<tr>
<th>Source</th>
<th>z</th>
<th>LAS_{rs} (kpc)</th>
<th>( t_{\text{int}} ) (h)</th>
<th>( L'_{\text{CO}} ) (K km s(^{-1}) pc(^2))</th>
<th>( M_{\text{H}<em>2} ) (M</em>{\odot})</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRC 0152-209</td>
<td>1.92</td>
<td>13</td>
<td>15.5</td>
<td>( 6.6 \pm 2.0 \times 10^{10} )</td>
<td>( 5 \pm 2 \times 10^{10} )</td>
</tr>
<tr>
<td>MRC 0156-252</td>
<td>2.09</td>
<td>68</td>
<td>11.0</td>
<td>( &lt; 2.3 \pm 0.7 \times 10^{10} )</td>
<td>( &lt; 2 \pm 0.6 \times 10^{10} )</td>
</tr>
<tr>
<td>MRC 0932-242</td>
<td>2.93</td>
<td>30</td>
<td>18.3</td>
<td>( &lt; 7.3 \pm 2.2 \times 10^{10} )</td>
<td>( &lt; 6 \pm 2 \times 10^{10} )</td>
</tr>
<tr>
<td>MRC 2025-218</td>
<td>2.63</td>
<td>40</td>
<td>17.4</td>
<td>( &lt; 2.5 \pm 0.8 \times 10^{10} )</td>
<td>( &lt; 2 \pm 0.6 \times 10^{10} )</td>
</tr>
<tr>
<td>MRC 2104-242</td>
<td>2.49</td>
<td>191</td>
<td>19.5</td>
<td>( &lt; 2.6 \pm 0.8 \times 10^{10} )</td>
<td>( &lt; 2 \pm 0.6 \times 10^{10} )</td>
</tr>
<tr>
<td>MRC 2224-273</td>
<td>1.68</td>
<td>( \leq 5 )</td>
<td>15.3</td>
<td>( &lt; 1.4 \pm 0.4 \times 10^{10} )</td>
<td>( &lt; 1 \pm 0.3 \times 10^{10} )</td>
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</table>
CO(1-0) survey of HzRG with ATCA/CABB

• First systematic survey of CO(1-0) in unbiased sample of HzRGs.

• Status (14 sample sources):

  • CO(1-0) only detected in compact radio sources, or outside the radio continuum (but low number statistics!)
    - CO(1-0) – molecular gas least affected by excitation/heating – at radii not affected by radio source??
    - Alignment CO(1-0) with radio jets? (e.g. Klamer et al 2004)

• Compare with ongoing EVLA CO(1-0) surveys:
  - high-z quasars/qso’s (Riechers et al 2011)
  - high-z submm galaxies (Ivison et al. 2011, Riechers et al 2011)
  - high-z starforming BzK galaxies
    (Aravena et al. 2010, see also talks by Helmut Dannerbauer, Manuel Aravena, Dominik Riechers)
Conclusions

• ATCA/CABB excellent southern instrument for complementary studies of high-z CO with ALMA
  • CO(1-0) observations with ATCA/CABB: most robust tracer for molecular gas at high-z (incl low-density, widespread, sub-thermally excited component).

• Ongoing systematic survey of CO(1-0) in HzRG
  • MRC 0152-209: strongest CO(1-0) signal in HzRG to date
  • Ideal for ALMA observations of high CO transitions of dense molecular gas
CO(1-0) survey of HzRG with ATCA/CABB

- CO(1-0) in z=1.92 radio galaxy MRC 0152-209

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Pentericci et al. (2000, 2001)  
Emonts et al. (2011), ApJL accepted (arXiv/….)

\[ M_{\text{H}_2} = 6 \times 10^{10} M_\odot \]  
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Feain et al. (2005)

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