Molecular Line Emission/Absorption From High-z Galaxies

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Outline

✓ Identify key unsolved problems where ATCA can have an impact
✓ Possible future proposals

1. Introduction and background
   - key issues for the distant universe
   - why the millimeter regime is important

2. Molecular emission lines at high-z
   - observability of CO lines
   - metallicity effects
   - known systems
   - what ATCA can do

3. Molecular absorption lines at high-z
   - observability
   - abundance ratios & confusion
   - redshift searches for absorption systems
   - temperature of the CMBR

4. Where can ATCA have an impact?
Species in the high-z galactic zoo:

- Quasars (both radio loud and radio quiet)
- Radio galaxies
- Lyman Break Galaxies (LBGs)
- EROs (Extremely Red Objects)
- Submm detected objects

- QSOs: some contain large amounts of molecular gas and dust
- Radio galaxies: some contain large amounts of molecular gas and dust
- LBGs: star forming galaxies, but small gas/dust masses
- EROs: partly old high-z elliptical galaxies, partly dusty high-z starbursts
- Submm galaxies: dusty, massive, high-z galaxies, unknown redshifts

Millimetre Science With the Upgraded Australia Telescope

Molecular Line Emission/Absorption From High-z Galaxies
Optically identified submm detected sources (only three so far)
Two of them have large molecular gas masses (seen through CO emission)

Dust continuum  CO(3-2) emission

AGN Type II

z = 2.81
(Frayer et al. 1999)

Starburst

z = 2.56
The star formation rate density as a function of

redshift

Look-back time

![Graphs showing star formation rate density as a function of redshift and look-back time.](image-url)
Observability of CO emission lines at high redshift

Observed ‘antenna temperature’ is the excess brightness temperature above the local temperature of the CMBR:

\[ \Delta T_b = [J(T_x) - J(T_{bg})](1 - e^{-\tau_v}) \]

where \( T_{bg} = 2.726(1 + z) \) K, and

\[ J(T) = \frac{h \nu / k}{\frac{h \nu}{e^{kT} - 1}} \]

In LTE \( T_x = T_k \)

\( \Delta T_b \) decreases with redshift for fixed \( T_x \).

The flux is then:

\[ S_v = \frac{2k}{c^2} v^2 \Delta T_b \]

Dust has a larger negative ‘K-correction’ than CO lines

\[ S_{dust} \propto v^4 T_{dust} \]

\[ S_{CO} \propto v^2 \Delta T_b \]
Cool and less dense

\[
\log(nH2) = 4 \quad \log(N_{\text{CO}}) = 18.5 \quad \text{TK} = 30
\]

Warm and dense

\[
\log(nH2) = 6 \quad \log(N_{\text{CO}}) = 19.5 \quad \text{TK} = 90
\]

Distribution of J-levels of CO for two different gas components at different redshifts (from Combes et al. 1999).

Distribution peaks for CO(4-3) and CO(5-4) transitions, with restfrequencies 461 and 576 GHz, respectively

Observable at 3mm for \( z > 3.6 \) and 4.7
Metallicity effects on the observability of CO (and other) molecules at high-z

From observations of nearby dwarf and low surface brightness galaxies it is known that CO and dust are underabundant (per blue luminosity, or galaxy mass) compared to normal spiral galaxies. This is likely to be an effect of low metallicity (low abundance of C, O and Si).

When the dust abundance is depleted by a factor 20

- $H_2$ is depleted by 10% (self-shielding)  
- CO is depleted by 95%  

(Maloney & Black 1988)

The conversion factor $X$ (molecules of $H_2$ per K km/s) depends nonlinearly on the metallicity $Z$. Possibly as $Z^{-2.2}$ (Arnault et al. 1988). This has been confirmed, at least for metallicities 1/10 solar.

CO emission becomes increasingly difficult to observe as the metallicity decreases.
Abundances from Damped Ly\(\alpha\) systems (Pettini et al. 1999)

Abundances at High Redshift \((z = 3)\)

(Pettini 2000)
The most distant CO and dust emitting source today: $z = 4.69$
<table>
<thead>
<tr>
<th>Name</th>
<th>Redshift</th>
<th>M(H$_2$)</th>
<th>M(dust)/M$_0$</th>
<th>L$_{FIR}$/L$_0$</th>
<th>Lensed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1202-725</td>
<td>4.69</td>
<td>9 $10^{10}$</td>
<td>2 $10^8$</td>
<td>1 $10^{12}$</td>
<td>?</td>
</tr>
<tr>
<td>BR0952-0115</td>
<td>4.43</td>
<td>3 $10^9$</td>
<td>3 $10^7$</td>
<td>1 $10^{12}$</td>
<td>YES</td>
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<tr>
<td>B1335-0414</td>
<td>4.41</td>
<td>1 $10^{11}$</td>
<td>detected</td>
<td>-</td>
<td>NO?</td>
</tr>
<tr>
<td>APM08279+5255</td>
<td>3.91</td>
<td>2 $10^9$</td>
<td>1 $10^7$</td>
<td>8 $10^{13}$</td>
<td>YES</td>
</tr>
<tr>
<td>4C60.07</td>
<td>3.79</td>
<td>8 $10^{10}$</td>
<td>2 $10^8$</td>
<td>2 $10^{13}$</td>
<td>NO</td>
</tr>
<tr>
<td>6C1909+722</td>
<td>3.53</td>
<td>4 $10^{10}$</td>
<td>2 $10^8$</td>
<td>2 $10^{13}$</td>
<td>NO</td>
</tr>
<tr>
<td>SMM0239-0136</td>
<td>2.81</td>
<td>8 $10^{10}$</td>
<td>detected</td>
<td>1 $10^{13}$</td>
<td>YES</td>
</tr>
<tr>
<td>MG0414+0543</td>
<td>2.64</td>
<td>5 $10^{10}$</td>
<td>detected</td>
<td>-</td>
<td>YES</td>
</tr>
<tr>
<td>SMM14011+0252</td>
<td>2.56</td>
<td>5 $10^{10}$</td>
<td>detected</td>
<td>3 $10^{12}$</td>
<td>YES</td>
</tr>
<tr>
<td>H1413+117</td>
<td>2.56</td>
<td>4 $10^{10}$</td>
<td>1 $10^8$</td>
<td>2 $10^{12}$</td>
<td>YES</td>
</tr>
<tr>
<td>53W002</td>
<td>2.39</td>
<td>1 $10^{10}$</td>
<td>weak cont</td>
<td>-</td>
<td>NO</td>
</tr>
<tr>
<td>F10214+4724</td>
<td>2.28</td>
<td>2 $10^{10}$</td>
<td>9 $10^8$</td>
<td>7 $10^{12}$</td>
<td>YES</td>
</tr>
<tr>
<td>Haro10</td>
<td>1.44</td>
<td>7 $10^{10}$</td>
<td>2 $10^8$</td>
<td>9 $10^{11}$</td>
<td>NO</td>
</tr>
</tbody>
</table>
What can be seen with the ATCA?

\[ v_{obs} = \frac{v_0}{1+z} \]

\[ v_{obs} : 84 - 115 \text{ GHz} \]

<table>
<thead>
<tr>
<th>transition</th>
<th>min redshift</th>
<th>max redshift</th>
<th>rest frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(1-0)</td>
<td>0.0</td>
<td>0.37</td>
<td>115.271</td>
</tr>
<tr>
<td>CO(2-1)</td>
<td>1.0</td>
<td>1.7</td>
<td>230.530</td>
</tr>
<tr>
<td>CO(3-2)</td>
<td>2.0</td>
<td>3.1</td>
<td>345.796</td>
</tr>
<tr>
<td>CO(4-3)</td>
<td>3.0</td>
<td>4.5</td>
<td>461.041</td>
</tr>
<tr>
<td>CO(5-4)</td>
<td>4.0</td>
<td>5.9</td>
<td>576.267</td>
</tr>
<tr>
<td>CO(6-5)</td>
<td>5.0</td>
<td>7.2</td>
<td>691.473</td>
</tr>
</tbody>
</table>
$T_{\text{sys}} = 350 \, \text{K}$, $N_A = 5$, $t_{\text{int}} = 10 \, \text{hours}$, dual polarization

$\Omega_{\Lambda} = 0.7$, $\Omega_m = 0.3$

$\Omega_{\Lambda} = 0.0$, $\Omega_m = 1.0$

$M(\text{H}_2)$ vs. Redshift $z$
Serendipitously discovered BAL QSO (Irwin et al. 1998) with a R magnitude of 15.2 at high redshift.

(Irwin et al. 1998)
PdB results for APM08279+5255

(Downes et al. 1999)
PdB results for APM08279+5255

(Wiklind et al. 2002)
- Low CO rotational levels in APM08279+5255
  - Papadopoulos et al. (2001) find CO(1-0) and CO(2-1) emission (with the VLA)
  - Extended emission (different from the high J-levels found by Downes et al. (1999)
  - Additional emission regions, not associated with APM08279+5255

from Papadopolous et al. 2001
What can be seen with the ATCA?

\[ \nu_{\text{obs}} = \frac{\nu_0}{1 + z} \]

\[ \nu_{\text{obs}} : 16 - 26 \text{ GHz} \]

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<tr>
<td>CO(1-0)</td>
<td>3.4</td>
<td>6.2</td>
<td>115.271</td>
</tr>
<tr>
<td>CO(2-1)</td>
<td>7.9</td>
<td>13.4</td>
<td>230.530</td>
</tr>
<tr>
<td>HCO⁺(1-0)</td>
<td>2.4</td>
<td>4.6</td>
<td>89.189</td>
</tr>
<tr>
<td>HCO⁺(2-1)</td>
<td>5.9</td>
<td>10.1</td>
<td>178.375</td>
</tr>
</tbody>
</table>
Molecular absorption, complimentary to emission

Molecular emission and absorption lines probe different types of molecular gas

Emission lines

$$\Delta T_b = [J(T_x) - J(T_{bg})](1 - e^{-\tau_v})$$

$$J(T) = \frac{h\nu}{k} \frac{h\nu}{e^{\frac{kT}{h\nu}} - 1}$$

$$S_v = \frac{2k}{c^2} v^2 \Delta T_b$$

Absorption lines

$$\int \tau_v \, dv = N_{tot} \frac{c^3}{8\pi v^3} \frac{g_J A_{J,J+1}}{f(T_x)} \propto \frac{N_{tot}}{T_x^2} \mu_0^2$$

- Emission is sensitive to warm (and dense) molecular gas
- Absorption is sensitive to cold (diffuse) molecular gas
HCO\(^+\)(1-0) absorption towards Centaurus A (Wiklind & Combes 1998)
HCO$^+$ (1-0) absorption towards Centaurus A with ATCA

I, $\tau = 204.0$ min, Bl = 3–4, T = 17:20:18

 Velocity (optical, Barycentric) (km/s)
Various molecular transitions in absorption at intermediate redshifts

CO(1-0) \( z = 0.25 \)

HCO+(2-1) \( z = 0.89 \)

HNC(2-1) \( z = 0.89 \)

C^{18}O(2-1) \( z = 0.68 \)

N$_2$H+(2-1) \( z = 0.89 \)

HCN(2-1) \( z = 0.67 \)
Measuring the temperature of the Microwave Background Radiation (CMBR)

Millimeter regime

Rotational transitions

Optical regime

Hyperfine structure transitions

\[ \frac{\Delta E}{k} = \frac{hc}{\lambda k} = T \approx 5 \text{ K} \]
Measuring the temperature of the Microwave Background Radiation (CMBR)

(Wiklind & Combes in prep)
Unsaturated absorption lines in PKS1830-211 at \( z = 0.89 \)

(Wiklind & Combes in prep.)
Measuring the temperature of the Microwave Background Radiation (CMBR)

\[ T_{CMBR} = T_0 (1 + z) \]
The Cloverleaf (H1413+117)

- Gravitationally lensed QSO
- Several different molecular transitions detected
- Line ratios model dependent (differential magnification?)

Barvainis et al. 1997
Kneib et al. 1997
Important issues for the high redshift universe

➢ The epoch of the first metal formation (= galaxy formation)
   Is there a galaxy formation epoch?

➢ The chemical evolution of the star forming gas
   Has star formation been the same at all cosmic times?

➢ The mass function of high redshift galaxies
   Molecular gas and dust measure mass better than optical/NIR light

➢ Redshift distribution of submm detected sources
   Important for all issues

➢ Galaxy correlation function as a function of redshift?
   Is there a galaxy-galaxy merging epoch?

➢ Hierarchical vs. monolithic galaxy formation scenarios
   How many of the E’s are formed through mergers?
Important issues for the high redshift universe

Continued from previous viewgraph ...

- Redshift distribution of submm detected sources
  Important for all issues

- The temperature of the CMB radiation as a function of redshift
  Test of quintessence models

- Gravitational lensing
  Statistics of strong lensing, weak lensing and unobscured view

- Large scale structure and cosmological parameters
  S-Z effect in clusters and CMB fluctuations on small scales
Relation between look-back time and redshift

\[ \frac{1}{H_0} \approx 13h^{-1}_{75} \text{ Gyrs} \]
Silk & Spaans: CO emission observable at any redshift at wavelengths longer than 1 mm.

Combes et al.: CO emission increasingly difficult to observe as $z$ increases (although still observable with an instrument like ALMA)

Different results because different assumptions of the gas distribution

Silk & Spaans assume a small mean optical depth – distributing Orion-like star forming regions over galactic scales

Combes et al. assume a high mean optical depth – molecular gas very centrally distributed in a manner similar to ULIRGs

Both groups assume fairly large galaxies, with $10^{10}$-$10^{11}$ $M_\odot$ of molecular gas, and a high metallicity