Exploration of High Redshift Galaxies through Intensity Mapping

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SMA Science in the Next Decade
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Exploring the Early Universe

Molecular gas, as the fuel for star formation, is a vital component of galaxies, and plays a crucial role in their evolution.

CO and [CII] are two of the principle tracers used for cold gas within galaxies.

Kulesa, C. 2011, Bolatto et al., 2013
CO Luminosity Function

Measuring CO/[CII] emission from a broad population of galaxies is important for measuring the abundance and evolution of molecular gas.

Constraints on CO at $z \sim 3$ are the product of 100 hours integration time with PdBI. *Even with this deep a measurement, these constraints are very weak!*

Walter et al., 2014
Large & Shallow Field
Intensity mapping shares a common methodology with CMB power spectrum production and analysis.
Think Big, Go Small!

The CO Power Spectrum Survey (COPSS)

SZA Dishes

COPSS Collaborators:

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**First (tentative) detection!** Power spectrum for CO constrained to $P_{CO} = 3.0^{+1.3}_{-1.3} \times 10^3 \, \mu K^2 \, (\text{Mpc}/h)^3$, $P_{CO} > 0$ to 98.9% confidence. Weak evidence ($\sim 1\sigma$) of increasing power with decreasing redshift.

Keating et al., 2016
A Tale of Two Regimes

Luminosity function of the form

$$\Phi_{CO}(L) = \phi^* \left( \frac{L}{L_*} \right)^\alpha e^{-L/L_*} \, dL \quad L > L_{min}$$

Normalization  Low L slope  High L Cutoff  Low L Cutoff

- **Clustering Power**: Sensitive to the broad population of galaxies (one molecule, one vote!)
- **Shot Power**: Sensitive to “luminous-but-common” systems, i.e., Milky Way-like galaxies.

Pullen et al., 2013  k-Mode (h$^2$ Mpc$^{-1}$)
CO Luminosity Function

Each side of the power spectrum measures a different moment of the luminosity function.

Walter et al., 2014
Most interferometers will only be sensitive to the shot component of the power spectrum

Walter et al., 2014
High-mass objects

Low-mass objects

At higher SNR, one can use frequency resolution to screen out more massive/luminous objects.

Walter et al., 2014
Direct imaging can also be used with intensity mapping experiments to search for rarer objects.

Walter et al., 2014
Luminosity function constraints can be significantly enhanced by direct detection experiments, even when few sources are detected.

Keating et al., 2016
Suitability of the SMA

- Compact nature means individual emitters not resolved (OPTIMAL)
- Smaller dishes/relatively larger field of view (OPTIMAL)
- Full SWARM correlator coming online (OPTIMAL)
- Broad frequency coverage (OPTIMAL)
- Only shot power component can be measured (NEUTRAL)
Combining CO and [CII] Results

- Combined constraints on CO/[CII] luminosity functions give insights into “luminous-but-common” galaxies
- Combined data can also allow for more robust estimates of cosmic H$_2$ density

**“SMGs all the way down”:**
Lots of dusty star-forming galaxies

**“Milky Way Miracle”:**
Early molecular gas resembles local galaxies

**“Primordial and Pristine”:**
Cold gas has little chemical enrichment

**“Lightly Dusted”:**
Some metal, little dust

Less CO

More CO

Less [CII]

More [CII]
Future CO/[CII] Intensity Mapping

The Millimeter Intensity Mapping Experiment (mmIME):
“It only looks like there’s nothing there”

VLA, ACA and SMA are well-suited for intensity mapping cross-correlation studies!

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Tzu-Ching Chang (ASIAA) Natalie Mashian (CfA)
Anastasia Fialkov (CfA) Dan Marrone (Arizona)
Can use CO to constrain cosmic molecular gas abundance out to $z \sim 5$ (and may be able to use [CII] to constrain $\rho(H_2)$ at higher redshift).
Cross-Correlation Studies

With a more limited measurement, can use models to estimate fraction of starburst/IR-luminous galaxies at high redshift.

With a deeper integration, one can measure individual line ratios, probe physical conditions of the molecular gas.

Sargent et al., 2014

Spilker et al., 2014
With a deeper integration, one can constrain the moderate/high-mass scaling relationship for CO/[CII] luminosity and molecular gas abundance.

Popping et al., 2015
Planning for the future

The sensitivity of intensity mapping experiments depends on:

- System Temperature ($\propto T_{sys}^2$)
- Bandwidth ($\propto B$)
- Configuration ($\propto R^{1/2}$)
- Systematics control ($\sim 20\%$?)

Other notes:
- Since the survey should be blind, choice of target fields is flexible
- Broad frequency coverage is a major boost for SMA IM studies
- Dual-pol doubles (!) sensitivity, affords extra systematics check
**Science Forecast and Conclusions**

- Intensity mapping studies with the SMA will be a powerful probe for molecular gas over a broad range of cosmic history.
- SMA upgrade would enable searches at much higher redshift.
- Upgrade would also allow for detailed studies of physical gas conditions and onset of quiescence in the early Universe.

<table>
<thead>
<tr>
<th>Pilot Survey (up to 100 hrs)</th>
<th>Existing Array (up to 1,000 hrs)</th>
<th>Upgraded Array (up to 10,000 hrs)</th>
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<tbody>
<tr>
<td>- First detection/confirmation of result from COPSS</td>
<td>- [CII] from 4 ≤ z ≤ 6</td>
<td>- [CII] from 4 &lt; z &lt; 10</td>
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<tr>
<td>- Molecular gas density at z ∼ 1, 2, 3</td>
<td>- CO from 0.2 ≤ z ≤ 3</td>
<td>- CO SLED from z ∼ 0.5 − 6</td>
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<tr>
<td>- Constraints on CO SLED at z ∼ 2</td>
<td>- Molecular gas density from z ∼ 1 − 5</td>
<td>- [Cl]/[NII]/[O1] cross-correlation studies</td>
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<td></td>
<td>- CO SLED constraints from z ∼ 1 − 3</td>
<td>- Physical gas conditions</td>
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<td>- Fraction of starburst-like objects as a function of redshift</td>
<td>- High-mass scaling relationships/history of quiescence</td>
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<td></td>
<td>- Molecular gas density from z ∼ 0.2 − 8</td>
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