(Dense) Molecular Gas & Star Formation in Galaxies

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Outline

- Motivations: dense gas as direct tracer of star-forming gas
- JCMT large program (MALATANG)
- Other examples & Future demands
DIFFERENT PHASES OF ISM

NGC 6946

embedded SF

24μm

unobscured SF

HI gas

HI

H₂ gas

CO

Kennicutt & Evans 2012, ARAA
Molecular gas drives cosmic star formation

(Riechers et al. 2019)

credit: ESA - C. Carreau
Molecular gas drives cosmic star formation

(Riechers et al. 2019)

CARILLI & WALTER 2014
Motivation: ISM & Star-formation

tracing dense gas — the direct fuel of SF

\[ \text{Transition} \quad \begin{array}{ccc}
\text{Transition} & n_{\text{crit}} [\text{cm}^{-3}] & E_J/k_B [\text{K}] \\
\text{CO}(1 - 0) & 4.4 \times 10^2 & 5.53 \\
\text{CO}(2 - 1) & 3.6 \times 10^3 & 16.60 \\
\text{CO}(3 - 2) & 1.3 \times 10^4 & 33.19 \\
\text{CO}(4 - 3) & 3.0 \times 10^4 & 55.32 \\
\text{CO}(5 - 4) & 5.9 \times 10^4 & 82.97 \\
\text{CO}(6 - 5) & 1.0 \times 10^5 & 116.16 \\
\text{CO}(7 - 6) & 1.5 \times 10^5 & 154.87 \\
\text{HCN}(1 - 0) & 1.7 \times 10^5 & 4.25 \\
\text{HCN}(2 - 1) & 1.6 \times 10^6 & 12.76 \\
\text{HCN}(3 - 2) & 5.2 \times 10^6 & 25.52 \\
\text{HCN}(4 - 3) & 1.3 \times 10^7 & 42.53 \\
\text{HCO}^+ (1 - 0) & 2.6 \times 10^4 & 4.25 \\
\text{HCO}^+ (2 - 1) & 2.6 \times 10^5 & 12.76 \\
\text{HCO}^+ (3 - 2) & 1.0 \times 10^6 & 25.52 \\
\text{HCO}^+ (4 - 3) & 2.5 \times 10^6 & 42.53 \\
\text{CS}(1 - 0) & 8.3 \times 10^3 & 2.35 \\
\text{CS}(2 - 1) & 7.9 \times 10^4 & 7.05 \\
\text{CS}(3 - 2) & 3.0 \times 10^5 & 14.11 \\
\text{CS}(4 - 4) & 7.7 \times 10^5 & 35.27 \\
\text{CS}(5 - 4) & 1.8 \times 10^6 & 49.37 \\
\text{CS}(6 - 5) & 3.1 \times 10^6 & 65.83 \\
\text{CS}(7 - 6) & 4.9 \times 10^6 & 65.83 \\
\end{array} \]
Star Formation relations

Gao & Solomon 2004a,b

Zhang et al. 2014; Wu et al. 2005
QUESTIONS TO ADDRESS

▸ Different environments: nuclear, arm, disk?
▸ Connection between local clouds and galaxies?
▸ Consistency and differences between tracers?
JCMT LARGE PROGRAM: MALATANG

Mapping the Dense molecular gas in the Strongest star-forming Galaxies

- HCN 4-3 and HCO$^+$ 4-3 survey toward 22 IR-bright galaxies
- 390 hours (Nov. 2015 – Jul. 2017)

Significance:

- Resolved dense gas SF relations
- Intermediate (sub-kpc) scales/luminosities
- Radial distribution of dense gas and SF efficiency

PI: Yu Gao (CN), Thomas Greve (UK) & Zhiyu Zhang (Germany)
co-I: Satoki Matsushita (Taiwan), Kotaro Kohno (Japan), Aeree Chung (South Korea), Christine Wilson (Canada), Qinghua Tan et al.
RESULTS (1) SF RELATION

- linear correlations hold for all densities $>10^4$ cm$^{-3}$!

- Bridge the gap between extragalactic (galaxy-integrated) and Galactic (single clouds) observations

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**Tan et al. (2018)**

**Chen+2015**

**Zhang+2014**
RESULTS (2): NGC 253

DENSE GAS IS CONCENTRATED

<table>
<thead>
<tr>
<th>concentration index</th>
<th>$r_{90}$</th>
<th>$r_{50}$</th>
<th>$r_{90}/r_{50}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>stellar</td>
<td>0.69 (0.08)</td>
<td>0.30 (0.12)</td>
<td>2.28 (0.92)</td>
</tr>
<tr>
<td>CO 1-0</td>
<td>0.6 (0.03)</td>
<td>0.31 (0.05)</td>
<td>1.94 (0.34)</td>
</tr>
<tr>
<td>CO 3-2</td>
<td>0.29 (0.06)</td>
<td>0.09 (0.08)</td>
<td>3.36 (3.32)</td>
</tr>
<tr>
<td>$L_{IR}$</td>
<td>0.44 (0.15)</td>
<td>0.11 (0.25)</td>
<td>3.86 (8.54)</td>
</tr>
<tr>
<td>HCN 4-3</td>
<td>0.17 (0.27)</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>HCO+ 4-3</td>
<td>0.32 (0.26)</td>
<td>…</td>
<td>…</td>
</tr>
</tbody>
</table>

offset along major axis (arcsec)  offset along minor axis (arcsec)

Jiang et al. (to be submitted)
for different transitions, stellar feedback has different effect?

(Usero et al. 2015, Bigiel et al. 2016, Gallagher et al. 2018a)

similar discussion in the CMZ (Central Molecular Zone):
Kauffmann et al. 2013, 2017; Kruijssen et al. 2014; Rathborne et al. 2015)
FOLLOW-UP PLAN

HCN & HCO⁺ (3-2), AND LARGER SAMPLE

- multi-J will better constraint SF properties
- new JCMT observations: M16AP028: 38 hrs; M19AP004: 50 hrs
- Scuba2 data (M16BP098)
- many available in archive
- ALMA archive can enlarge the sample to southern sky
FOLLOW-UP POTENTIALS: 
CONNECT GALACTIC AND EXTRAGALACTIC STUDIES

- the large FOV of JCMT and the high resolution of ALMA (or SMA) are great complement to each other
MALATANG focuses on sub-kpc scale

Exploring the effect of stellar feedback.
EXAMPLES

- M51: EMPIRE (30m, Bigiel et al. 2016)
  89 GHz, 75h, RMS: ~15 mJy, 4’x6’

- NGC253: (MALATANG – JCMT)
  354 GHz, 20 h, RMS: ~ 100 mJy, 2’x2’ covered

- NGC253: ALMA (16 antennas)
  100 GHz, 3-point and 7-point mosaic, 1.5’ covered (Meier+ 2015, Leroy+ 2015)

- NGC1068 ALMA (18 – 27 antennas)
  2h, 11-field mosaic in band 7 and 1-point in band 9 (García-Burillo+ 2014, Viti+2014)

- ULIRGs (45 antennas)
  z=0.05 ~ 0.15 (HCN 3-2, 1 mJy, Imanishi et al. 2019)

HIGH SENSITIVITY AND RESOLUTION!
**WIDE BAND**

- **wide band!**
  - higher SNR,
  - higher efficiency
  - more accurate line ratios

- **many physical/chemical properties**
  - embedded
  - isotopes, shocks, temperatures …
  - (Zhang et al. 2018, nature)

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**similar upgrade for JCMT as the SMA?**
DATA ARCHIVE

- data growing faster than community
- “data mining” more challenging
- need data center in China?
SUMMARY OF DREAMS

- Wide band (and stable baseline)
- High sensitivity (large dish)
- Large FOV (heterodyne array)
- Urgent need of fast archive access