The MALATANG survey: dense gas and star formation in nearby star-forming galaxies

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On behalf of the MALATANG team
OUTLINE

• Background and Motivation
• The MALATANG survey
  - Science goals
  - Sample and Observations
  - Results
• Summary and Follow-up plans
**MOTIVATION**

Which phases of gas are directly connected to star formation?

Scaling relations between gas and SF: \( \log L_{\text{IR}} = \alpha L'_{\text{gas}} + \beta \)

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**Kennicutt-Schmidt law**

\[ \text{total gas} = \text{HI} + \text{H}_2 \]

- **dense gas**
  - \((\text{HCN J}=1-0, \rho_{\text{cut}} \sim 3 \times 10^4 \text{ cm}^{-3})\)
  - SFR = \(1.8 M^1_{\text{dense}} / 10^8\)
  - **linear correlation:** constant dense gas SF efficiency in galaxies; the dense molecular gas is directly connected to SF
**MOTIVATION**

Whether dense gas forms stars is sensitive to the local environment?

IRAM 30m – EMPIRE (3-4mm dense gas tracers)

- The conditions in a galaxy disk set the gas density distribution and that the dense gas traced by HCN shows an environment-dependent relation to star formation
MOTIVATION

How the gas properties affect their ability to form stars?

Slope of $\log(L_{IR})$-$\log(L'_{gas})$ vs. molecular line critical densities

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<table>
<thead>
<tr>
<th>Transition</th>
<th>$n_{\text{crit}}$ [cm$^{-3}$]</th>
<th>$E_{J}/k_{B}$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$(1-0)$</td>
<td>$4.4 \times 10^{2}$</td>
<td>5.53</td>
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<tr>
<td>CO$(2-1)$</td>
<td>$3.6 \times 10^{3}$</td>
<td>16.60</td>
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<td>CO$(3-2)$</td>
<td>$1.3 \times 10^{4}$</td>
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<td>CO$(4-3)$</td>
<td>$3.0 \times 10^{4}$</td>
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<td>CO$(5-4)$</td>
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<td>CO$(7-6)$</td>
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<td>HCN$(2-1)$</td>
<td>$1.6 \times 10^{5}$</td>
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<td>HCN$(3-2)$</td>
<td>$5.2 \times 10^{5}$</td>
<td>25.52</td>
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<tr>
<td>HCN$(4-3)$</td>
<td>$1.3 \times 10^{6}$</td>
<td>42.53</td>
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<tr>
<td>HCO$^+$(1-0)</td>
<td>$2.6 \times 10^{4}$</td>
<td>4.25</td>
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<td>HCO$^+$(2-1)</td>
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<td>HCO$^+$(4-3)</td>
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<tr>
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<td>$3.1 \times 10^{6}$</td>
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<tr>
<td>CS$(7-6)$</td>
<td>$4.9 \times 10^{6}$</td>
<td>65.83</td>
</tr>
</tbody>
</table>

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Zhang, Gao et al. (2014)
MALATANG

https://www.eao.hawaii.edu/MALATANG

Mapping the dense molecular gas in The strongest star-forming Galaxies

- JCMT Large Program – M16AL007 & M20AL022 (~40% complete)
- PIs: Yu Gao, Zhiyu Zhang, Thomas Greve
- A 400+400 hours (band 3 to 4) campaign on the JCMT using the HARP array to map HCN & HCO\(^+\) \(J=4-3\) in 28 of the nearest and IR-brightest galaxies beyond the local group
- First attempt at systematically map the distribution of dense gas out to large galactocentric distances in a statistically significant sample

SCIENCE GOALS

- Resolved dense gas star formation relations
- Intermediate scales/luminosities
- Different environments: nuclear vs. disk
- Radial distribution of dense gas and SF efficiency
- Dense gas excitation as a function of environment
SAMPLE & OBSERVATIONS

- $S(60\mu m)>50$ Jy and $S(100\mu m)>100$ Jy in RBGS(Sanders+03) and $\delta>-40$ deg
- In total 28 IR bright nearby galaxies
The MALATANG Survey: the Lgas-L_{IR} correlation on sub-kpc scale in six nearby star-forming galaxies (Tan et al. 2018)
The mean $L_{IR}/L_{dense}$ ratio appears to vary little across the whole population of sample galaxies

- Significant scatter in $L_{IR}/L_{dense}$ ratio (~0.36 dex for whole galaxies)
- $L_{IR}/L_{dense}$ increases with $L_{IR}$ for individual spatially resolved galaxies
The MALATANG Survey: dense gas and star formation from high transition HCN and HCO$^+$ maps of NGC 253 (Jiang et al. 2020)

- SFE$_{dense}$ increases with higher stellar surface density, inconsistent with the results using HCN J=1-0 data.
- The existing stellar components might have different effects on the high-J HCN and HCO$^+$

J = 4-3

J = 1-0
The MALATANG Survey: dense gas and star formation in NGC 1068 (Lin et al. 2022, submitted)
The relationship between $\text{SFE}_{\text{dense}}$ and [Cl] excitation (Jiao et al., in prep.)

Jiao et al. 2017, 2019
The relationships between dense gas, infrared emission, and radio continuum on sub-kpc scale in galaxies (Tan et al. in prep.)

MALATANG II – 3x3 Jiggle

Maffei 2
PACS 70μm

HCN (4-3)

Sorai et al. 2012

Maffei 2 1.56 GHz (Jy beam⁻¹)

NRO45m: CO (1-0)

Sorai et al. 2012
The relationships between dense gas, infrared emission, and radio continuum on sub-kpc scale in galaxies (Tan et al. in prep.)

VLA L-band Radio Continuum

- NGC 253 1.42 GHz (Jy beam⁻¹)
- NGC 1068 1.41 GHz (Jy beam⁻¹)
- IC342 1.57 GHz (Jy beam⁻¹)
- M82 1.43 GHz (Jy beam⁻¹)
- Maffei2 1.56 GHz (Jy beam⁻¹)
- M51 1.42 GHz (Jy beam⁻¹)
- M83 1.45 GHz (Jy beam⁻¹)
- NGC 6946 1.57 GHz (Jy beam⁻¹)
The relationships between dense gas, infrared emission, and radio continuum on sub-kpc scale in galaxies (Tan et al. in prep.)
SUMMARY

• Dense gas and star formation in spatially resolved galaxies at sub-kpc scale
  - linear correlation, extend the relation to an intermediate luminosity regime
  - systematic variations of $SFE_{\text{dense}}$ with $L_{\text{IR}}$ within individual galaxies

• Detailed studies on NGC 253 and NGC 1068
  - $SFE_{\text{dense}}$ traced by high-J HCN/HCO$^+$ increases with higher stellar surface density, inconsistent with the results based on HCN J=1-0

• The relationship between $SFE_{\text{dense}}$ and [CI] excitation

• Relationships between dense gas, star formation, and radio continuum
  - tight correlation between dense gas and RC
  - a rising trend for IR/RC as a function of $SFE_{\text{dense}}$, IR-RC relation may have a dependency on the local environment

FOLLOW-UP PLANS

• Observations
  - JCMT SCUBA-2 & HCN/HCO$^+$ J=3-2
  - High resolution SMA/ALMA maps
  - Herschel archive: high-J CO, [CI] data
  - APEX high-J HCN/HCO$^+$/CS lines

• Modelling:
  - LVG & PDR modelling of SF regions
  - reproducing observed relations and line ratio

Thank you!