MALATANG project updates: the far-infrared and HCN correlations

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MALATANG in a nutshell: here illustrated by a study of M51 (Chen et al. 2015). a) Moment 0 map of the HCN J=1 – 0 emission towards M 51 (contours at: 0.1, 0.6, 1.9, 3.4, 4.9, 5.4 K km/s on the Tmb scale). b) Herschel/PACS 70 μm image tracing the IR dust continuum (contours at: 3, 9, 27, 81 mJy/pixel. c) The resolved L_{IR} – L’_{HCN J=1-0} relation observed towards M 51, with each symbol representing a region ~1 kpc in size. The solid and dashed lines show the best log-linear fits to the nuclear (filled triangles) and disk (open triangles) regions combined and to the disk regions only, respectively. The combined correlation is seen to be shallower than the galaxy-integrated linear relation observed by Gao & Solomon (2004) (illustrated by the dashed line). d) Schematic of a HARP-B jiggle mode observations of a MALATANG target (NGC 253). With a beam spacing of 1000 , the shown 3 x 3 jiggle pattern will result in fully sampled HCN and HCO+ J = 4 -3 maps that probe dense molecular gas across a range of environments, from inter-arm regions to the central starburst nuclei.
**PROJECT AND SCIENCE GOALS**

- 390hr JCMT-HARP program: map HCN and HCO+ J=4-3 in 23 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
- Dense gas vs. star formation relationship down to gas masses of $\sim 5 \times 10^6 M_\odot$ and scales $\sim 0.2-2.8\text{kpc}$ in other galaxies
- Bridge the gap between and Galactic observations

- Resolved dense gas star formation relations
- Intermediate scales/luminosities
- Different environments: nuclear vs. disk
- Radial distribution of dense gas and SF efficiency
**Motivation**

Kennicutt & Evans 2012, ARAA

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**Diagram a**

- Galaxy type
- Normal/irregular
- Low surface brightness
- Infrared-selected
- Circumnuclear
- Metal-poor

**Diagram b**

- LIRGs/ULIRGs $L_{IR} > 10^{11} L_\odot$
- Normal spirals

Disk-average [SFR\~ density(HI+H2)^1.4]
SFR vs. M(H2): No Unique Slope: 1, 1.4, 1.7?

The fit lines: SFR = 1.4M(H2)/10^9 for SFR < 20M☉yr⁻¹ and SFR = 7.6(M(H2)/10^9)^{1.73} for all

- Normal Spirals
- LIRGs/ULIRGs, L_IR > 10^{11}L☉
- Literature ULIRGs/LIGs

HI ~ H2

HI-dominated LSB galaxies

Extragalactic SF=CO until 90’s


H2-dominated LIRGs/ULIRGs
SF thresholds may simply reflect the change of the dominant cold gas phase in galaxies from HI $\rightarrow$ H$_2$ & from H$_2$--$\rightarrow$ denseH$_2$ $\rightarrow$ dense cores (DCs) $\rightarrow$ super-star clusters (SSCs)

Schruba+2011 $\sim$ linear in H$_2$!
arXiv:1502.08001

\[
\log \Sigma_{SFR} \ (M_\odot \ yr^{-1} \ kpc^{-2}) = \log \Sigma_{dense} \ (M_\odot \ pc^{-2}) + N
\]

\(N = 1.0\)

\(\triangle - \text{Normal Spiral}\)

\(\blacktriangle - \text{(U)LIRGs}\)
SFR vs. $M_{\text{dense}}(\text{H}_2)$: linear correlation

The fit line: $\text{SFR} = 1.8M_{\text{dense}}/10^6$ for $\text{SFR} < 20\ M_\odot\ \text{yr}^{-1}$

- LIGs/ULIGs $L_{\text{IR}} > 10^{11}L_\odot$
- Normal Spirals

Baan, Henkel, Loenen + 2008

HCN, CS, HNC etc. in SF gals.

- Baan et al. (2008)
- Solomon et al. 1992
- Nguyen et al. 1992
- Henkel et al. 1990
- Henkel, Baan, Mauersberger 1991

Best case studies: Arp 220 & NGC 6240 (Greve + 2009)
The fit line: \( \frac{L_{\text{FIR}}}{L_{\text{HCN}}} = 700 \)
for \( L_{\text{IR}} < 10^{11}L_\odot \)

\[ L_{\text{FIR}} = L_\odot \]
Wu, Evans, Gao et al. 2005 ApJL

Wu+2010

Fit to GMCs

Fit to Galaxies

Fit to both GMCs & Galss..
Chen, Braine, Gao et al. 2017
(arXiv: 1612.00459)
Star Formation Rate ($M_\odot$yr$^{-1}$) vs. Mass of dense gas ($M_\odot$)

- Gao & Solomon 2004
- Chen et al. 2015 (M51, inner)
- Chen et al. 2015 (M51, outer)
- Lada et al. 2010 (Extinction)
- Longmore et al. 2013 (CMZ)
- Chen et al. 2017 (M51, GMA)
- Brouillet et al. 2005 (M31)
- Buchbender et al. 2013 (M33)
- Chin et al. 1997, 98 (SMC, LMC)

This paper

Shimajiri + 2017
These new surveys do fill in the luminosity range between whole galaxies and individual clouds. The HCN-IR (dense gas-SFR) correlation holds in broad brush.

Leroy’s talk at Sexten 17

New surveys:
- Disk pointings
- M51 pixels
- M82 regions
- Antenna pointings
- ALMA disk profiles

**Molly Gallagher, Leroy et al. (submitted), Bigiel et al. (2016), Usero et al. (2015)**
EMPIRE Result

Jiménez-Donaire et al. 2019
Connecting with Galactic CS study ~ 10 orders of magnitude

CS J=5-4

Galaxies

N=1.0

SMT 10m
IRAM 30m
Baan + 2008

Galactic cores

N=1.0
Connecting with Galactic CS study ~ 10 orders of magnitude

CS J=2-1

\[ N = 1.07 \pm 0.03 \]

\[ N = 1.0 \]

Galaxies

IRAM 30m

Galactic cores

\[ N = 1.0 \]

Wu+2010

22 Apr. 2012, PMO, Zhi-Yu Zhang
Zhang, Gao, Henkel et al. 2014

CS $J=7\rightarrow6$, $N = 1.00\pm 0.06$
Correlation Coefficient: 0.98

HCN $J=4\rightarrow3$, $N = 1.06\pm 0.06$
Correlation Coefficient: 0.98

HCO$^+$ $J=4\rightarrow3$, $N=1.10\pm0.05$
Correlation Coefficient: 0.96

CS $J=7\rightarrow6$

$Y=1.00 \times 3.98$

$Y=0.91 \times 4.91$

$Y=1.00 \times 4.00$
Warm CO Gas Emission as a SFR Tracer

\[
\text{SFR}/(M_\odot \text{ yr}^{-1}) = 1.34 \times 10^{(-5\pm0.12)} \left(\frac{L_{\text{CO}(7-6)}}{L_\odot}\right)
\]

(based on Kennicutt 1998)

Advantages over \(L_{\text{IR}}\):

- Not much contaminated by AGN (Lu et al. 2014)
- Easier to measure in the ALMA era, i.e., only need one line measurement in principle

Possible caveats:

- NGC 6240-like objects. But they are quite rare.
- Low metallicity combined with low gas density may lead to low CO abundance due to a more severe UV photo-dissociation.

(Note: only plotted the 102 GOALS LIRGs with at least 85% of the 70um flux within the 30" FTS beam)
All are not far from linear
– dense gas law

CO J~6-7 are the tightest
– best SF tracer

Slightly super-linear at J≤6 – K-S law

High-J CO better tracers dense gas!

D. Liu, Y. Gao, K. Isaak, et al. 2015
CO(5-4) – FIR from Local to High-z

CO(5-4) a most detected high-J CO line at high-z – deepest CO toward normal SFG at z~1.5
Daddi et al. 2015

BzK – normal SFG with moderate SFR – steady evolution

SMG – starburst with very high SFR – merger evolution – note that IR are poorly determined so far
$L_{\text{IR}}$ vs. $L'_{\text{HCN}(4-3)}$

HCN $J=4\rightarrow3$
Slope = $1.01\pm0.01$, $R=0.99$
- Zhang et al. (2014)
- Liu et al. (2016)
- NGC 253
- NGC 1068
- IC 342
- M82
- M83
- NGC 6946

$L_{\text{IR}}$ vs. $L'_{\text{HCO}^+ (4-3)}$

HCO$^+$ $J=4\rightarrow3$
Slope = $1.07\pm0.04$, $R=0.96$
- Zhang et al. (2014)
- NGC 253
- NGC 1068
- IC 342
- M82
- M83
- NGC 6946
The MALATANG Survey: the $L_{\text{gas}} - L_{\text{IR}}$ correlation on sub-kiloparsec scale in six nearby star-forming galaxies

Jiggle-mapping: $2 \times 2$ arcmin$^2$ central region

The dense gas traced by HCN(4-3) and HCO$^+$(4-3) is linearly correlated with the IR emission on sub-kpc scales.

1. higher $f_{\text{dense}}$ in NGC253 center and in higher $\Sigma_{\text{SFR}}$

2. SFE vs. $\Sigma_{\text{star}}$ seems different from Bigiel+06
   (explanation: $n_{\text{crit}}$ of 4-3 is 100 times higher than $n_{\text{crit}}$ of 1-0. Hence tracing denser gas)
Stacking in M82
Wang, J (MS thesis)

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<th>CO J=3-2 central frequency (MHz)</th>
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<td>345468</td>
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$L'_{\text{dense}} - L_{IR}$ relation

![Graph showing the relationship between $L'_{\text{dense}}$ and $L_{IR}$ for various galaxies, including those from Tan et al. 2018.]
EMPIRE used the IRAM 30-m telescope to map multiple molecular lines of nine nearby, face-on massive spiral galaxies. The J=1→0 transitions of HCN, HCO+, HNC, CO, 13CO, C18O, and other fainter lines were covered.

Three EMPIRE galaxies have been also observed in MALATANG (NGC 2903, NGC3627, NGC6946).

The EMPIRE survey spent about 70 hours per galaxy and achieved an r.m.s. noise level of 2-3 mK (T.)

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<td>15:47:00</td>
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<td>NGC 5194</td>
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<td>NGC 6946</td>
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<td>243</td>
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<td>42.4</td>
<td>8.40</td>
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<td>21×10^{-3}</td>
<td>10.5</td>
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</table>

Jiménez-Donaire et al. 2019
EMPIRE Result

Jiménez-Donaire et al. 2019
New JCMT Proposal

- We have proposed to extend the MALATANG to map HCN J=4→3 and HCO+ J=4→3 in all EMPIRE galaxies including 5 JIGGLE maps with JCMT.

- We need a total of 476 hours band 3 time to reach an r.m.s. noise level of 2-3 mK (T_A).
New APEX Proposal

- We have proposed to use the SEPIA345 receiver on APEX to map the HCN (4-3), HCO+ (4-3), CS (7-6), and CO (3-2) simultaneously along the major axes of five nearest/brightness Southern galaxies with declination < -40 degree.

- We need a total of 79 hours under the weather condition of 1.0mm pwv.
Summary

• Dense Molecular Gas $\rightarrow$ High Mass Stars
• SFR $\sim M($DENSE$), \text{ linear?! dense gas
• Dense gas tracers (e.g. HCN, CS, HCO$^+$ COJ$>3$, H2O… density $>\sim 10^5$ cc), linear!
• HI $\rightarrow$ H$_2$ $\rightarrow$ DENSE H$_2$ $\rightarrow$ Stars
  Schmidt law : HI(gas reservoir) $\rightarrow$ Stars $\times$
  Kennicutt : HI(gas reservoir) + H$_2$(fuel ?!) $\rightarrow$ Stars $\times$
  Gao & Solomon: Dense H$_2$ (fuel !!) $\rightarrow$ Stars!? 

from Cores to High-z: Dense Gas $\rightarrow$ Massive SF

*HCN/HCO+(4-3) still the linear correlation with far-IR: globally and
resolved regions provided by MALATANG
*Variations and scatters in the linear correlations: physics!
*Sino-German collaboration grants: synergy empire/malatang/paws