ALMA Exploration of Dense Warm Molecular Gas & Cold Dust in Nearby LIRGs

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(A GOALS Project)

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A Herschel FTS Survey of LIRGs in GOALS

- GOALS: The Great Observatories All-Sky LIRG Surveys
- 200+ LIRGs ($L_{\text{IR}} \geq 10^{11} L_\odot$), selected from IRAS archive
- $f_{60\mu m} > 5.24 \text{ Jy}, z < 0.088$
- Surveys: Spitzer, HST, Chandra X-ray, GALEX, Herschel, …

- Herschel SPIRE FTS spectroscopy (194 – 671 µm) of 125 LIRGs (including 32 from Herschel archive).
- A flux limited subset of GAOLS: $F_{\text{IR}} > 6.5 \times 10^{-13} \text{ W/m}^2$.
- Warm CO line emission in mid-J ($5 \leq J \leq 10$) is clearly driven by on-going star formation in majority of LIRGs and ULIRGs.
- As a result, CO (6-5) is a good SFR tracer.

CO (6-5) vs. $L_{\text{IR}}$ (Lu+2014)
Our ALMA Cycle-0 Project

• Band 9: CO (6-5) line emission and dust continuum at 435 µm
• Angular resolution: ~ 0.25” (combining E and C configurations)
• Spectral (kinematic) resolution: 7 km/s

Main science goals:
• How does the warm gas distribute in LIRG nuclei?
• How tight does it correlate spatially with star formation?
• Outflows: How important? Difference between AGN & SB?
• In LIRGs with AGN: when is AGN dominant in dust & gas heating?

Targets selection criteria:
• Close LIRGs in GOALS: D < 85 Mpc (good spatial resolution)
• Best band-9 transmission during transit: -38°<Dec<-8°
• Strong nuclear activity: >50% of f_{mir} is in nucleus (r<0.5 kpc)

Targets observed:
• NGC 34: D = 84 Mpc (0.25” ~ 100 pc), with a Sy2 nucleus
• NGC 1614: D = 68 Mpc (0.25” ~ 80 pc), starburst
NGC 34: major merger, starburst & AGN

- $L_{IR} = 10^{11.49} L_\odot$
- $D = 84$ Mpc ($0''.25 \sim 100$ pc)
- Major-merger ($m/M \sim 1/2 - 1/3$), coalesced
- Sy2 nucleus: $L_{X,2-10Kev} = 1.4 \times 10^{42}$ ergs/s

NGC 1614: minor merger, starburst

- $L_{IR} = 10^{11.65} L_\odot$
- $D = 67.8$ Mpc ($0''.25 \sim 80$ pc)
- Minor merger ($m/M \sim 1/5$)
- No AGN?
ALMA Maps:
(all maps are 5”×5” in size)

NGC 34:
• compact nuclear disk (resolved)

NGC 1614:
• circum-nuclear ring
• clumpy
• no nucleus

CO SLEDs of the two LIRGs:

NGC 34:
AGN contribution <19%

NGC 1614:
AGN contribution <28%
Integrated CO(6-5) contour map on HST V-band image (beam ~ 0.1")

NGC 34: $f = 1004 \pm 151$ Jy km/sec
(recovered ~100% of single dish flux)

On CO(1-0) image (CARMA) (Fernandez+2014)
CO(1-0) beam (2''.48 x 2''.14)

FWHM of the emission: 0''.5 (~ 200 pc)
NGC34: CO 6-5 line emission: channel maps

$1\sigma = 5.5\text{mJy/beam}$

$\delta v = 34 \text{ km/sec}$

$1''$

22.08.14 Vienna 2014
NGC 34: spectrum & an emission feature

H^{13}CN(8-7): PDR models with mechanical heating

- Mean $v$: $v_{\text{outflow}} = 400$ km/s
- Outflow rate: $32 \, M_{\odot}$/yr

(assume $X_{\text{CO}}$ of ULIRGs)

aperture: $r=1''$

contour map of the feature

CO(6-5) peak

solution: $T \sim 200$ K, $n \sim 1 \times 10^5$, $N(\text{H}^{13}\text{CN})/N(\text{CO}) \sim 0.001$


22.08.14
NGC1614

(All images are overlaid by the same CO (6-5) contours)

no Compton-thick AGN ($N_H < 1 \times 10^{23}/cm^2$)
NGC 1614: Channel maps

Velocity distribution

No molecular outflows.
Cold gas (CO (2-1)) is more extended than warm gas (CO (6-5)).

Much of cold gas is not associated with SFR (indicated by radio).
CO (6-5) compared with radio (8.4 GHz) and Pa-α

(All images are overlaid by the same CO (6-5) contours)

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thermal: extinction-corrected Pa-α
Gas and SFR not strongly correlated (in particular around the nucleus).

CO(6-5) correlates much better with nonthermal than with thermal radio.
Summary

• Our ALMA Band 9 observations resolved the CO (6-5) in LIRG nuclei, down to ~100 pc linear scale, for the first time.
• In the two LIRGs observed, the CO (6-5) emission has very different distributions: in NGC 34 it is in a compact nuclear disk (size ~ 200 pc) while in NGC 1614 it is in a circum-nuclear ring.
• The warm gas probed by CO (6-5) is more compact than cold gas probed by low-J CO lines, and has stronger spatial correlation with the SFR (as indicated by radio continuum). Much of the cold CO is not associated with the current star formation.
• For NGC 34, an emission feature in the red wing of the line profile can be due either to a warm gas outflow with outflow rate of $32 \, M_{\odot}/yr$ (assuming ULIRG conversion factor), or to the H$^{13}$CN(8-7) line emission.
• No evidence for any molecular outflows in NGC 1614.
• In NGC 34, an unresolved central core contains 19% of the CO (6-5) and 28% of the continuum, indicating an insignificant contribution from the AGN to both emissions.
• For NGC 1614, a Compton-thick AGN is ruled out by the non-detection of the nucleus in the dust continuum.
• In NGC 1614, the CO (6-5) has a significantly stronger spatial correlation with the non-thermal radio than with the thermal radio, consistent with theoretical models assuming the mechanical heating powered by SNs dominates the heating of warm dense gas.
• More LIRGs will be observed in CO (6-5) in ALMA Cycle-2 with even better angular resolution!