Radiative and mechanical feedback in the molecular gas in (Ultra)Luminous Infrared Galaxies

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Outline

- Review of early SPIRE/FTS results
- CO as a probe of what?
- Tracing molecular gas mass
At $z=0.042$, one of the closest QSOs ($D_L=192$ Mpc)

With $L_{IR} = 4\cdot10^{12} L_\odot$, the most luminous ULIRG in the IRAS Revised bright Galaxy Sample

“Warm” infrared colours

Star-forming disk ($\sim500$ pc radius) + absorbed X-ray nucleus

Face-on molecular disk, $M_{H_2} \sim 5\cdot10^9 M_\odot$

(Van der Werf et al., 2010)
CO excitation in Mrk231

2 PDRs + XDR  6.4:1:4.0

- High-J lines require XDR
- Low-J lines powered by star formation.

* 28 erg cm^{-2} s^{-1} \rightarrow G_0=10^{4.2}
H₂O excitation in Mrk231

- Radiative pumping dominates
- H₂O probes the temperature and intensity of the local IR radiation field

(González-Alfonso et al., 2010)
NGC6240 – shocked gas

- LIRG, merger, 2 nuclei separated by 1.8"
- Molecular gas concentrated between the nuclei
- Gas excitation mostly by shocks/dissipation of mechanical energy
- Bright H$_2$ emission confirms this
CO lines in NGC6240

- High excitation CO ladder
- Very high Line/Cont ratio
- Shock excitation dominates

(Meijerink et al. 2013)
CO ladders: excited or shocked?

- CO ladders of Mrk231 (X-ray excited) and NGC6240 (shocked) are very similar

(Meijerink et al., 2013)

Taken by itself, the CO ladder is not a clean probe of physical processes! Addition information is needed (an often available).
CO ladders: general trends

- CO excitation increases with $L_{\text{IR}}$ and $F_{60}/F_{100}$
- Colour: warm gas and warm dust correlate
- Multiple excitation components always present in starburst galaxies/LIRGs/ULIRGs

(see Greve et al. poster)

Feedback in molecular gas in (U)LIRGs

(see also Lu et al. poster)
NGC 253

- Nearby starburst
- 2.5 Mpc (1'' ≈ 12 pc)
- Starburst in inner 200 pc
- $L_{\text{FIR}} = 2 \times 10^{10} L_\odot$

Feedback in molecular gas in (U)LIRGs
NGC253: SPIRE/FTS

(Rosenberg et al., in prep, and talk at this conference)
**NGC253 CO ladder**

- Simultaneous fit to $^{12}$CO, $^{13}$CO, HCN and HNC ladders

- Three excitation components required

- >70% of CO emission from high-excitation component

- Excitation mechanism?

Feedback in molecular gas in (U)LIRGs
CO excitation in NGC253

- Photon heating (PDRs) is not sufficient to produce the medium and high excitation gas components in NGC253

- Additional heating: mechanical (dissipation of turbulence) or cosmic rays; cf., Bradford et al. (NGC253), Rangwala et al. (Arp220)

- Chemistry (HCN/HNC) favours mechanical heating

- Mechanical heating is the dominant heating mechanism for the warm gas in NGC253

- The need for additional heating is a general result for starbursts/LIRGs/ULIRGs
Sources of mechanical heating

- Supersonic turbulence is very dissipative

- \( M_{\text{gas}} = 10^{11} M_\odot, \Delta v = 400 \text{ km/s}, \) dissipated over a crossing time in a ULIRG:

\[
L_{\text{mech}} \approx 10^{12} L_\odot \approx L_{\text{IR}}
\]

- What drives this turbulence? Large-scale shocks, outflows, stellar winds, SN explosions, radiation pressure?

Feedback in molecular gas in (U)LIRGs

outflows: talks by Sturm, Fischer, poster by Spoon, etc.
Water as a probe

- Radiative pumping of H$_2$O lines: derive local FIR flux
- Combine with $T_d$: implies emission at the blackbody limit
- $\Rightarrow$ Infrared-opaque ($\tau_{100\mu m} \approx 1$) central regions
- Radiation pressure from the strong IR radiation field:
  \[ P_{rad} \approx \tau_{100} \sigma T_d^4 / c \]
- Can be dominant pressure term and source of local turbulence
**CO and molecular gas mass**

- Converting CO flux (luminosity) into H$_2$ column density (mass):

\[
X = \frac{N(H_2)}{I(CO)} = c_1 \left( \frac{n(H_2)}{200 \text{ cm}^{-3}} \right)^{1/2} \left( \frac{T_{\text{line}}}{6K} \right)^{-1}
\]

\[
\alpha = \frac{M(H_2)}{L'(CO)} = c_2 \left( \frac{n(H_2)}{200 \text{ cm}^{-3}} \right)^{1/2} \left( \frac{T_{\text{line}}}{6K} \right)^{-1}
\]

(MW: $\alpha=4$; ULIRGs: $\alpha=0.8$)

(U)LIRG sample low-$J$ lines only

(Papadopoulos, Van der Werf, Isaak & Xilouris, 2012)
**X-factors based on low CO lines only**

**Assumptions:**
- One gas component
- Based on low-\(J\) CO lines only

**Results:**
- \(\alpha\)-values cluster between 0.5 and 1 with tail up to and exceeding Milky Way values

**But:**
- Higher CO lines and density tracing lines reveal a substantial dense gas component

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(Papadopoulos, Van der Werf, Isaak & Xilouris, 2012)
Molecular gas masses in NGC253

- The three components have comparable $H_2$ masses!

- Low-$J$ CO lines alone miss a significant amount of molecular gas

- In ULIRGs, most mass may be in high-excitation component, not seen in low-$J$ lines – to be verified
Tracing molecular gas mass

- **Warning:** discussions of this have been the death-blow for many conferences.

- **CO:**
  - Need to deal with CO-dark molecular gas: [CII] – requires abundance and modelling
  - Need multi-line data from 1-0 (2-1) to at least 9-8
  - Need additional information to beat down degeneracies (e.g., HCN)
  - Use of $^{13}$CO to get at CO optical depth is problematic due to possibly redshift-dependent abundance ratio
  - Calibration based on CO, [CI], HCN and $L_{\text{IR}}$ may be feasible but still needs much work

(Danielson, Swinbank et al., astro-ph/1309.5952)
Can we use dust emission instead?

- To derive $M_{\text{gas}}$ from $M_{\text{dust}}$ a dust/gas ratio is always needed

- A CO molecule is always a CO molecule, but dust grains at low and high redshift likely have different properties

- Need long-wavelength data (ALMA) in order to avoid to probe cool dust and avoid possible optical depth effects near continuum peak

- Need also short-wavelength data to determine $T_d$ – but confusion at Herschel resolution (see Swinbank talk)

- Multiple temperature components difficult to disentangle
The CO ladder probes the thermal state of the molecular gas, in particular cooling of the warm molecular gas.

Prominent AGNs produce high-J CO lines, but so do shocks.

In star-forming galaxies, photon-heating is typically insufficient to account for the heating of the warm molecular gas; additional (and dominant) heating by cosmic rays or mechanical energy input is needed.

Mechanical energy input and enhanced cosmic ray fluxes lead to chemical differences which can be separated observationally.

There can be significant mass in warm CO, which is not traced by low-J CO lines.