Dense gas in ULIRGs

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Credits

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“Simple people who think that they can learn astronomy by only looking at the stars, without knowledge of mathematics, will in a future life become birds.”

(Plato, Τιμαιος)
Outline

- ULIRGs and their integrated molecular gas properties
- molecular gas tracers in ULIRGs
- star formation laws
- thermal balance in molecular gas in ULIRGs
  - case study: Mrk 231
- outlook: the HerCULES project
The starburst bestiary

GEHRs
SSCs
HII galaxies
ELGs
CNELGs
W-R galaxies
BCGs
BCDs
LIGs, LIRGs
ULIGs, ULIRGs
LUVGs, UVLGs
nuclear starbursts
circumnuclear starbursts
clumpy irregular galaxies
Lyα galaxies
E+A galaxies
K+A galaxies
LBGs
DRGs
EROs
SCUBA galaxies
SMGs

\[ b \equiv \frac{\text{SFR}}{\langle \text{SFR} \rangle} \gg 1 \]

(Dense gas in ULIRGs)

(Kennicutt 2005)
Simple-minded estimate of "maximum star formation rate"

In the absence of external pressure, the maximum star formation rate occurs when a gas mass is turned into stars on the free-fall timescale.

\[ \dot{M}_{\text{max}} = \frac{M_{\text{gas}}}{t_{\text{ff}}} = M_{\text{gas}} \sqrt{G \rho} \]

selfgravitating sphere: \[ R^2 = \frac{3}{4} \frac{\sigma^2}{\pi G \rho} \]

\[ \Rightarrow \dot{M}_{\text{max}} \approx 100 \left( \frac{\sigma}{100 \text{ km/s}} \right)^3 M_0 \text{ yr}^{-1} \]
Starformation efficiency

- Starbursts cannot be simply scaled up.
- More intense starbursts are also more efficient with their fuel.

\[
\frac{L_{\text{IR}}}{L_{\text{CO}}} \propto \frac{\text{SFR}}{M_{\text{H}_2}} \propto \text{SFE}
\]

ULIRGs: \( \left< \frac{L_{\text{FIR}}}{M_{\text{H}_2}} \right> \approx 100 L_0 M_0^{-1} \)

Milky Way: \( \approx 1.5 L_0 M_0^{-1} \)

Galactic GMCs: \( \approx 1.8 L_0 M_0^{-1} \)

OMC-1: \( \approx 54 L_0 M_0^{-1} \)

Orion BN-KL: \( \approx 400 L_0 M_0^{-1} \)

\( L_{\text{IR}} \propto \text{SFR} \)
More dense gas means more efficient star formation.

$L_{IR}/L_{CO} \propto SFR/M_{H_2} \propto SFE$

$L_{HCN}/L_{CO} \propto$ mass fraction of dense gas

(Gao & Solomon 2001)
ULIRGs are morphologically messy

Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2

Dense gas in ULIRGs

(Evans et al.)
…but normally have well-ordered nuclear gas kinematics

(Downes & Solomon 1998)
Molecular gas in ULIRGs

- CO 1–0 reveals large gas masses, concentrated in compact structures (disks or rings), typically < 1 kpc in radius (Downes, Solomon, Radford, Scoville, …)

- X-factor converting CO luminosity into H$_2$ mass is subject of endless debate, since

\[ X \propto \frac{\sqrt{n}}{T_b} \]

- In ULIRGs a factor of 4 below “normal” is often adopted (Downes, Solomon, et al). Uncertain!

- Higher CO lines trace gas that is both warm and dense. Resulting H$_2$ masses (e.g., for high-z galaxies) are then even more uncertain.
Density or chemistry?


- PDR/XDR models disagree:
  - Maloney et al 1996: HCN/HCO$^+$ ratio enhanced in XDRs
  - Meijerink & Spaans 2006, 2007: HCN/HCO$^+$ ratio suppressed in XDRs
Dense vs. diffuse gas: the Antennae

[CII] widespread, CO J=7→6 isolated!

Dense gas in ULIRGs

SPIFI/JCMT
(Isaak, Nikola, Stacey, & Van der Werf, in prep.)
A fundamental tracer of star forming gas?

\[ \log[L_{IR}](L_{\odot}) = 1.02X + 2.79 \]

\[ \log[L'_{HCN1-0}](K \text{ km s}^{-1} \text{ pc}^2) = 1.00X + 2.9 \]

(Wu et al.)

starbursts, (U)LIRGs

Galactic starforming cores

One relation!
Star formation laws: \( L_{\text{IR}} \propto L_{\text{line}}^\alpha \)

- Using CO 1–0, we get \( \alpha \sim 0.8 \)
- Using HCN 1–0 or CO 3–2, we get \( \alpha \sim 1.0 \)

What do higher density tracers show?
HCO$^+$ 4—3 in Mrk 231 (10hrs JCMT)
HCN 4–3 in UGC 5101 (12hrs JCMT)

(Papadopoulos, Isaak, & Van der Werf, in prep.)
Star formation laws: $L_{\text{IR}} \propto L_{\text{line}}^\alpha$

- Using CO 1–0, we get $\alpha \sim 0.8$
- Using HCN 1–0 or CO 3–2, we get $\alpha \sim 1.0$

What do higher density tracers show?

- Using HCN 3–2, we get $\alpha \sim 0.7$ (Bussman et al., astro-ph)
- Using HCN 4–3, we get $\alpha \sim 0.6$ (Papadopoulos, Isaak, & Van der Werf, in prep.)
Implications

- Inconsistent with simple picture of a density threshold of a few $10^4$ for tracing star forming gas.

- However, a model of star formation in molecular clouds with:
  - lognormal density distribution (e.g., from supersonic turbulence)
  - Kennicutt-Schmidt star formation law with exponent $\sim 1.5$: $\sum_{SFR} \propto \sum g^{1.5}$
  - can account for this (Krumholz & Thompson 2007, Narayanan et al., 2008)

- Explanation of the resulting star formation laws:
  - Low-$L_{IR}$ galaxies have a large contribution from sub-thermally excited line emission
  - High-$L_{IR}$ galaxies have large amounts of gas with $n>n_{crit}$
Probing dense molecular gas

<table>
<thead>
<tr>
<th>Line</th>
<th>$T_{\text{ex}}$ [K]</th>
<th>$n_{\text{crit}}$ [cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO 1→0</td>
<td>5.5</td>
<td>1.7⋅10$^3$</td>
</tr>
<tr>
<td>CO 4→3</td>
<td>55</td>
<td>8.0⋅10$^4$</td>
</tr>
<tr>
<td>CO 6→5</td>
<td>116</td>
<td>2.5⋅10$^5$</td>
</tr>
<tr>
<td>HCN 1→0</td>
<td>4.3</td>
<td>1.4⋅10$^5$</td>
</tr>
<tr>
<td>HCN 4→3</td>
<td>42</td>
<td>5.5⋅10$^6$</td>
</tr>
</tbody>
</table>

molecular gas

temperature of dense gas

dense molecular gas
Mid-\(J\) CO lines in Mrk231

Mrk231 CO 6→5 and 4→3
RxW/JCMT  
(Papadopoulos, Isaak & Van der Werf 2007)

Dense gas in ULIRGs

Model based on CO 1→0 to 4→3 and 6→5

Model based only on CO 1→0, 2→1 & 3→2
Mid-$J$ CO lines probe dense gas

- **diffuse phase**: $T \approx 50-85$ K, $n \approx 300-10^3$ cm$^{-3}$ – up to CO 3–2
- **dense phase**: $T \approx 50-65$ K, $n \approx 10^4$ cm$^{-3}$ – CO 4–3 and higher

- Total gas mass is dominated by the **dense** component:
  \[ M \approx 1.5-3.5 \cdot 10^{10} M_\odot. \]
Thermal balance of the dense gas

**Arp 220:** \( \frac{L_{[\text{CII}]} }{L_{\text{FIR}}} \approx 1.3 \cdot 10^{-4} \)  
(cf. normal galaxies: \( 10^{-2} \rightarrow 3 \))

⇒ what cools the dense gas?  
**NB:** [CI] 609 mm not suppressed  
(Gérin & Phillips 1999)

Cooling budget in Mrk231

<table>
<thead>
<tr>
<th>Line</th>
<th>$L_{\text{line}}$ [$L_\odot$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[C II] 158 μm</td>
<td>$3.6 \cdot 10^8$</td>
</tr>
<tr>
<td>[C I]</td>
<td>$3.4 \cdot 10^6$</td>
</tr>
<tr>
<td>CO diffuse</td>
<td>$5.8 \cdot 10^6$</td>
</tr>
<tr>
<td>CO dense</td>
<td>$&gt;1.5 \cdot 10^8$</td>
</tr>
</tbody>
</table>

- CO cooling from the dense phase approaches [C II] cooling
- Consistent with dense PDRs
- Solution to the [C II] problem
- Full understanding crucial in ALMA era
Summary and outlook

- Although optically messy, molecular gas in ULIRGs normally show ordered motion.
- Hence they can be analysed using the “normal” tools such as Kennicutt-Schmidt type star formation laws.
- The observed CO/HCN line vs. IR correlations are consistent with a KS-law in a turbulent ISM with lognormal density distribution.
- Beware of PDR/XDR chemistry affecting abundances of HCN, HCO$^+$ and others
- Mid-$J$ CO lines are excellent probes of warm, dense gas, which forms the dominant mass component in objects studied in detail.
- Integrated CO emission comparable to [CII] in ULIRGs. Thermal budget suggests dense PDRs are dominant.
- Explore the low-$z$ universe in mid-$J$ CO lines: HerCULES
Who is HerCULES?

Paul van der Werf (Leiden; PI)
Susanne Aalto (Onsala)
Peter Ade (Cardiff)
Lee Armus (Spitzer SC)
Vassilis Charmandaris (Crete)
Aaron Evans (Stony Brook)
Jackie Fischer (NRL)
Yu Gao (Purple Mountain)
Eduardo Gonzalez-Alfonso (Henares)
Thomas Greve (MPIA)
Rolf Güsten (MPIfR)
Andy Harris (U Maryland)
Chris Henkel (MPIfR)
Kate Isaak (Cardiff)
Frank Israel (Leiden)
Carsten Kramer (Cologne)
Steve Lord (NASA Herschel SC)

Jesus Martín-Pintado (Madrid)
Joe Mazzarella (IPAC)
Rowin Meijerink (Berkeley)
Padelis Papadopoulos (Bonn)
Sabine Philipp (DLR)
Adam Rykala (Cardiff)
Dave Sanders (U Hawaii)
Giorgio Savini (Cardiff)
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Gordon Stacey (Cornell)
Sylvain Veilleux (U Maryland)
Cat Vlahakis (Leiden)
Fabian Walter (MPIA)
Axel Weiss (MPIfR)
Martina Wiedner (Cologne)
Manolis Xilouris (Athens)
What is HerCULES?

- **Herschel Comprehensive (U)LIRG Emission Survey**
- HerCULES is an approved Herschel Open Time Key Program to uniformly and statistically measure the neutral gas cooling lines in a flux-limited sample of (U)LIRGs.

**Sample:**
- all IRAS RBGS ULIRGs with $S_{60} > 12.19$ Jy (6 sources)
- all IRAS RBGS LIRGs with $S_{60} > 16.8$ Jy (23 sources)

**Observations:**
- SPIRE/FTS full high-resolution scans: 200 to 670 $\mu$m at $R \approx 600$, covering CO 5–4 to 13–12 and [CI] (+ other lines?)
- PACS line scans of [CII] and both [OI] lines
- All targets observed to same (expected) S/N
- Extended sources observed at several positions
Why HerCULES?

- develop use of the CO rotational ladder as a diagnostic
- inventory of neutral gas cooling
- statistically robust approach
- low-z benchmark for future ALMA observations
PDRs vs. XDRRs

- Identical incident energy densities give very different CO spectra
- Very high J CO lines are unique XDR tracers
- Need full coverage of CO ladder in real galaxies

(Spaans & Meijerink 2008)
A local benchmark for high-z galaxies

Even in ALMA era, often limited spatial resolution on very high z galaxies, but many lines available

HerCULES will provide an empirical framework for interpreting these data.

(Walter, Weiß et al.)
<table>
<thead>
<tr>
<th>Target</th>
<th>log($L_{\text{FIR}}/L_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mrk 231</td>
<td>12.51</td>
</tr>
<tr>
<td>IRAS F17207—0014</td>
<td>12.39</td>
</tr>
<tr>
<td>IRAS 13120—5453</td>
<td>12.26</td>
</tr>
<tr>
<td>Mrk 273</td>
<td>12.14</td>
</tr>
<tr>
<td>IRAS F05189—2524</td>
<td>12.20</td>
</tr>
<tr>
<td>Arp 299</td>
<td>11.88</td>
</tr>
<tr>
<td>NGC 6240</td>
<td>11.85</td>
</tr>
<tr>
<td>IRAS F18293—3413</td>
<td>11.81</td>
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<td>Arp 193</td>
<td>11.67</td>
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<tr>
<td>IC 1623</td>
<td>11.65</td>
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<tr>
<td>NGC 1614</td>
<td>11.60</td>
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<td>NGC 7469</td>
<td>11.59</td>
</tr>
<tr>
<td>NGC 3256</td>
<td>11.56</td>
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</table>

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<thead>
<tr>
<th>Target</th>
<th>log($L_{\text{FIR}}/L_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 4687/4686</td>
<td>11.55</td>
</tr>
<tr>
<td>NGC 2623</td>
<td>11.54</td>
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<tr>
<td>NGC 34</td>
<td>11.44</td>
</tr>
<tr>
<td>MCG+12—02—001</td>
<td>11.44</td>
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<tr>
<td>Mrk 331</td>
<td>11.41</td>
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<td>IRAS 13242—5713</td>
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<td>NGC 7771</td>
<td>11.34</td>
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<td>Zw 049.057</td>
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<td>NGC 5135</td>
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<td>IRAS F11506—3851</td>
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<td>NGC 2146</td>
<td>11.07</td>
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<tr>
<td>NGC 7552</td>
<td>11.03</td>
</tr>
<tr>
<td>NGC 1365</td>
<td>11.00</td>
</tr>
</tbody>
</table>

Dense gas in ULIRGs

+Arp 220, NGC 1068, NGC4418 from GTO