Mid – Infrared and Millimeter Spectroscopic Diagnostics of Local Luminous Infrared Galaxies

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& the GOALs collaboration

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The comoving number density of infrared luminous galaxies has increased by a factor of ~100 between 0<z<1.

By z~1.0 LIRGs produce half of the total comoving infrared luminosity density.
The Great Observatories All-sky LIRG Survey (GOALS)

• Spitzer Legacy Program-- targets 202 LIRG, 248 nuclei, in the local (z<0.088), Universe selected from the IRAS Revised Bright Galaxy Sample (Armus et al 2009)

• http://ssc.spitzer.caltech.edu/legacy/goalshistory.html

Data sets:
• Spitzer MIPS, IRAC, imaging (PI: Mazzarella)
• IRS spectroscopy (PI: Armus),
• HST ACS (PI: Evans),
• HST NICMOS (PI: Surace),
• GALEX (PI: Mazzarella, Howell),
• Chandra (PI: Sanders),
• optical and radio (literature)
• undergoing mm CO(1-0) CARMA obs (PI: Petric)
• Palomar NIR spectroscopy (PI: Petric)
Three questions

Question 1: Where does the IR come from, e.g. AGN/SB contribution to the IR luminosity from MID-IR spectroscopy

Question 2. What are the properties of the warm and cold molecular gas in LIRGs?

Question 3. How do major mergers shape the answers to 2 and 1?
Mid-infrared spectra in galaxies can arise from:

1. The emission from the ionized interstellar gas
2. Nonthermal emission from radio sources
3. Dust particles: from very small grains and PAH

Empirically the contribution of these can be disentangled.


• In 19% of LIRGs AGNs contribute more than 50% of the MIR nuclear emission
Contribution of SB/AGN to the nuclear MIR luminosity

- 23% [NeV] 14.3 µm detections
- 3% AGN contributes more than 50% to the nuclear MIR luminosity
- 51% [OIV] 25.98 µm are detected
- 4% more than 50% of their MIR nuclear emission comes from an AGN
Variables

1. zero point definitions
2. continuum under the PAH feature (line dependent)
3. differences between the projected slit sizes
4. differential extinction between [NeV], [OIV], and [NeII] (not important for our sources since [NeV]/IR and [NeV]/[NeII] yield similar results)
5. Bolometric corrections
In local LIRGs star formation is the main energy supplier to the bolometric luminosity

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>% of sources with AGN contributions to the bolometric luminosity more than 50%</th>
<th>Total AGN/Total bolometric luminosity for the sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>[NeV]/[NeII]</td>
<td>9%</td>
<td>10%</td>
</tr>
<tr>
<td>[OIV]/[NeII]</td>
<td>10%</td>
<td>12%</td>
</tr>
<tr>
<td>6.2 µm PAH /5.5 µm continuum</td>
<td>11%</td>
<td>13%</td>
</tr>
</tbody>
</table>

IRAC colors and Average Spectra

Color color AGN selection would miss at least half of AGN (Petric et al. 2011)
Combine with 30 to 15 micron continuum ratios
• **Morphology:** Spiral, Elliptical, Disturbed spiral, Disturbed elliptical, Double Nuclei, Hard to tell

• **Environment:** number of neighbors within one arcminute

• **Stage:** undisturbed, early stage, first encounter, mid-stage, late stage

45–50% merging galaxies

Cox & Loeb 2008
AGN contribution versus merger stage

- AGN fraction increases slightly with merger stage

Petric et al. 2011
Warm Molecular Gas

• MIR-lines probe rotational transitions of warm molecular gas at temperatures between ~100-1000K

• $^2\text{H}_2$ (S0 J = 2-0) 28.812 $\mu$m 39%
• $^2\text{H}_2$ (S1 J = 2-1) 17.035 $\mu$m 94%
• $^2\text{H}_2$ (S2 J = 4-2) 12.279 $\mu$m 33%
• $^2\text{H}_2$ (S3 J = 5-3) 9.665 $\mu$m 70%
• $^2\text{H}_2$ (S4 J = 6-2) 8.025 $\mu$m <1%
• $^2\text{H}_2$ (S5 J = 7-3) 6.910 $\mu$m 4%
• $^2\text{H}_2$ (S6 J = 8-6) 6.109 $\mu$m 0%
• $^2\text{H}_2$ (S7 J = 9-7) 5.511 $\mu$m 2%

### Table 2. $^2\text{H}_2$ Detection Statistics

<table>
<thead>
<tr>
<th>Line</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Median</th>
<th>Standard Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S(0) [10^{-17} W/m^2]</td>
<td>0.85</td>
<td>26.15</td>
<td>4.08</td>
<td>2.92</td>
<td>3.96</td>
</tr>
<tr>
<td>LS(0) [10^6 L_\odot]</td>
<td>1.11</td>
<td>138.15</td>
<td>11.92</td>
<td>7.01</td>
<td>17.81</td>
</tr>
<tr>
<td>S(1) [10^{-17} W/m^2]</td>
<td>0.64</td>
<td>16.59</td>
<td>31.45</td>
<td>5.11</td>
<td>369.94</td>
</tr>
<tr>
<td>LS(1) [10^6 L_\odot]</td>
<td>0.45</td>
<td>240.83</td>
<td>78.24</td>
<td>14.31</td>
<td>822.43</td>
</tr>
<tr>
<td>S(2) [10^{-17} W/m^2]</td>
<td>1.69</td>
<td>101.00</td>
<td>27.94</td>
<td>6.36</td>
<td>48.75</td>
</tr>
<tr>
<td>LS(2) [10^6 L_\odot]</td>
<td>3.48</td>
<td>224.52</td>
<td>64.64</td>
<td>24.54</td>
<td>107.00</td>
</tr>
<tr>
<td>S(3) [10^{-17} W/m^2]</td>
<td>7.81</td>
<td>56.50</td>
<td>4.22</td>
<td>3.14</td>
<td>5.51</td>
</tr>
<tr>
<td>LS(3) [10^6 L_\odot]</td>
<td>3.48</td>
<td>224.52</td>
<td>64.64</td>
<td>24.54</td>
<td>107.00</td>
</tr>
<tr>
<td>S(4) [10^{-17} W/m^2]</td>
<td>0.17</td>
<td>125.60</td>
<td>15.47</td>
<td>7.92</td>
<td>22.71</td>
</tr>
<tr>
<td>LS(4) [10^6 L_\odot]</td>
<td>2.10</td>
<td>122.00</td>
<td>25.36</td>
<td>12.00</td>
<td>39.65</td>
</tr>
<tr>
<td>S(5) [10^{-17} W/m^2]</td>
<td>1.15</td>
<td>398.77</td>
<td>108.13</td>
<td>52.24</td>
<td>146.69</td>
</tr>
<tr>
<td>LS(5) [10^6 L_\odot]</td>
<td>1.07</td>
<td>42.70</td>
<td>12.42</td>
<td>6.60</td>
<td>17.13</td>
</tr>
<tr>
<td>S(7) [10^{-17} W/m^2]</td>
<td>0.59</td>
<td>94.92</td>
<td>27.25</td>
<td>14.67</td>
<td>38.39</td>
</tr>
<tr>
<td>LS(7) [10^6 L_\odot]</td>
<td>1.07</td>
<td>42.70</td>
<td>12.42</td>
<td>6.60</td>
<td>17.13</td>
</tr>
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</table>
Shocked Molecular Gas—significant coolant in merging systems

$LH_2/L24\mu m \text{ SQ } \sim 100$

Median $LH_2/L24\mu m$ for LIRGs 0.003, max 0.5

Appleton et al. 2006
Guillard et al. 2009
Cluver et al. 2010
PAH and Warm Molecular Gas Tracers

- Warm H$_2$ correlates with 6.2 $\mu$m PAH emission
- Scatter suggests that PDRs provide the power used for H$_2$ excitation in only $\sim$85% of sources, the other source may be slow shocks as seen in nearby systems (Roussel et al. 2007)

- Correlation scatter does not change significantly with merger state
• Warm H$_2$ correlates with the [SiII] cooling line
• F(S0-S2)/F([Si II]) ranges between 0.08 to 0.8 with a median of 0.25 similar to SINGS galaxies
• Median F([SiII])/TIR $\sim$ 7 x 10$^{-4}$ consistent with PDR models of Kaufman et al. 2006 for $\sim$80% of sources, slightly higher value suggest shock excitation
• Correlation scatter increases slightly with H$_2$ Luminosity and with merger stage but is not enhanced by the presence of an AGN
• 8 resolved sources $S(0)$ and $S(1)$, one AGN dominated, 10% $S(1)$

• No obvious relation between the widths of the H2 profiles and the AGN contribution to the IR luminosity.

• See also Dasyra et al. 2011, Guillard et al. 2012
CO (1-0) with the Combined Array for Millimeter Astronomy

- 6-8 hours per source at a resolution of 1-3 Kpc
- 15-84 km/sec channels
- $3 \times 10^8$ M☉
- $30 - 50$ M☉/pc²
• CO (single dish flux recovered within 20-30%) traces the peaks in IR intensity
• Median molecular gas surface density $\sim 200 \, M\odot/pc^2$, [80-1000]
Example: II Zw 96

- Peak surface density
  1000 M☉/pc²

CO Peak located in region where Inami et al. (2010) find that 80% of IR emission originates

- 1.2 x 10^{10} M☉ Gas

- SFR 120 M☉/yr

- ~10^{7} years to finish the gas reservoir at these rates
• CO(1-0) emission regions vary in size from 2 Kpc to 20 Kpc

• 70–~2000 M/pc²

• Surface densities range widely within individual galaxies and average surface densities also vary significantly in galaxies in the same apparent interaction stage
Molecular Gas in Interacting Galaxies

- Average cold gas surface density and SFR both increase as the merger progresses.

- Depletion times do not appear to vary with stellar mass.

- However the total amount of cold gas does not appear to decrease with merger stage (converted quickly from HI?).
Three Answers

**Q1: AGN/SB contribution to the IR luminosity**
- 10% of local LIRGs are AGN dominated and 12% of the total bolometric Luminosity in local LIRGs comes from AGN.
- LIRGs with a significant AGN contribution have, higher median total L24 μm, warmer (f5/f24 nuclear) and (f24/f70) colors and are at later merger stage (Yuan et al. 2010, Petric et al. 2011).

**Q2. Molecular gas properties**
- Warm H$_2$ detected in 95% of sources, H$_2$ masses range between $10^{6-8}$ M$\odot$ and temperatures between 100 - 1000K correlate slightly with L IR and merger stage.
- Wider range in total H$_2$ to IR ratios than in ULIRGs but similar to normal galaxies.
- Tight correlations with [SiII] and 6.2 PAH μm flux suggest H$_2$ mostly associated with PDRs but 15% of LIRGs seem to require an additional heating mechanism.
- Molecular gas surfaces average ~200 M$\odot$/pc$^2$ but up to ~2000 M$\odot$/pc$^2$ increase with interaction stage and appear independent of stellar mass (Petric et al. in prep).

**Q3. Mergers**
- Higher AGN/SB fraction, higher IR luminosities and warmer nuclear colors.
- Highest rotational transitions S(5), S(7) are found in mergers, all sources with resolved H$_2$ lines with $\sigma > 350$ km/sec are mergers.
- Highest cold molecular gas surface densities are found in mergers.
- Ratio of Warm to Cold molecular gas also increase with merger stage.
Distribution of (S1) profile widths for interacting and non-interacting LIRGs

Median widths larger in interaction stages >2
Nuclear warm $H_2$ Masses

black – isolated galaxy  △ early stage or unclear  merging

- Weak correlation between the mass and IR luminosity
- Mergers require multiple temperature components
- No correlation between the mass and the AGN contribution to the IR
Average Spectra

The average spectrum of sources with an AGN looks similar to the average spectrum of sources without an AGN, but it has lower PAH emission and a flatter MIR continuum.
IRAC colors

• Color color AGN selection miss at least half of AGN.

>50% AGN
>25% AGN
Ultraluminous Infrared Galaxies

• 30-50% of ULIRGs are AGN dominated (Armus et al. 2006, Farrah et al. 2007, Veilleux et al. 2009)

Seyfert 1
Seyfert 2
LINER
HII-like
Normal Galaxies

- 5% AGN dominated (Goulding et al. 2009)
Nuclear $H_2$ temperatures

- No obvious correlation between merger stage and excitation temperature but highest $S(3)$ and Tex components seem to be found in mergers
- Slightly larger scatter for AGN dominated LiRGS, no correlation between the mass and the AGN contribution to the IR
- Warm $H_2$ masses range between $10^6-8$ M☉
Three Answers

Q 1: Where does the IR come from, e.g. AGN/SB contribution to the IR luminosity from MID-IR spectroscopy?
• 10% of local LIRGs are AGN dominated and 12% of the total bolometric Luminosity in local LIRGs comes from AGN
• LIRGs with low 6.2 μm PAH EQW (<0.27 μm) detections are
  • -higher median total 24 μm luminosity
  • -warmer (f5/f24 nuclear) and (f24/f70) colors
  • -later merger stage (Yuan et al. 2010, Petric et al. 2011)

Q2. What are the properties of the warm and cold molecular gas in LIRGs?
• Warm H\textsubscript{2} detected in 95% of sources, H\textsubscript{2} masses range between 10\textsuperscript{6-8} M\textsubscript{\odot} and temperatures between 100 - 1000K correlate slightly with L IR and merger stage
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• Molecular gas surfaces average ~200 M\textsubscript{\odot} /pc\textsuperscript{2} but up to ~4000 M\textsubscript{\odot} /pc\textsuperscript{2} increase with interaction stage and appear independent of stellar mass (Petric et al. in prep)

Q3. How do major mergers shape the answers to 2 and 1?
• Late stage mergers have higher AGN/SB fraction, higher IR luminosities and warmer nuclear colors.
• Highest cold molecular surface densities are found in mergers
• Ratio of Warm to Cold molecular gas also increase with merger stage, highest rotational transitions S(5), S(7) are found in mergers, all sources with resolved H\textsubscript{2} lines are mergers
The fraction of nuclear warm gas to total cold gas increases with SFR, but does not change with interaction stage => most of the warm H$_2$ heated by PDR not by shocks associated with interactions.
Using average between ULIRG and Galactic conversion factor

-> Median value $M = 5 \times 10^9 \, M_\odot \, \text{H}_2$
Three Answers

Q1: AGN/SB contribution to the IR luminosity
- 10% of local LIRGs are AGN dominated and 12% of the total bolometric Luminosity in local LIRGs comes from AGN
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- Highest rotational transitions S(5), S(7) are found in mergers, all sources with resolved H$_2$ lines are mergers
PAH and Warm Molecular Gas Tracers

- S(1) intensity does not appear to change with the fractional contribution of the AGN to the IR
Measuring Temperatures and Masses in MIR

\[ N_i = \frac{\text{flux}(i)}{A(i) \times h \times \nu(i)} \times \frac{4\pi}{\text{beam}} \]

\[ \frac{N_i}{N} = \frac{g(i)}{Z(T_{ex})} \times \exp \left( -\frac{T_i}{T_{ex}} \right) \]

g(i) and Ti are the statistical weight and energy level of that state, Z is the partition function.

\[ N_i \] is the column density of H₂.
Measuring Temperatures and Masses in MIR

$N_i$ is the column density of $H_2$ in the $i$-th state

g(i) and $T_i$ are the statistical weight and energy level of that state, $Z$ is the partition function
20% of sources show evidence for grain processing
Predominantly in early merger stages [1-3]
$\frac{[\text{NeIII}]}{[\text{NeII}]} < 2.5$ as in normal galaxies (Bernard-Salas 2009) but lower than the range measured in radio-galaxies (Guillard et al. 2012)
6.2 µm PAH EQW versus 24 µm emission

• Unlike ULIRGs, local LIRGs show no tight correlation between 24 µm luminosity and the 6.2 µm PAH EQW.  (Petric et al. 2011)