Herschel/SPIRE FTS View of M82
Probing the molecular ISM in M82 starburst

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M82 SPIRE FTS observations

- M82 is the nearest (3.9Mpc) starburst (~10Msun/yr)
  - Brightest IRAS extragalactic source (1390Jy at 100µm)
  - Widely used in cosmology as starburst prototype
- Target of the Very Nearby Galaxies Survey (SAG2)
- M82 was observed as Performance Verification target
  - High resolution (FWHM=0.048 cm\(^{-1}\) R~1000)
  - 1332 seconds (10 repetitions)
  - Point source mode (single staring pointing)
Data analysis

- Processed with customized version of HIPE3 pipeline
  - We used only data of central detectors
  - M82 was detected also on first ring detectors
- Beam size of the FTS bolometers varies with wavelength
- Spatial extent of the M82 central starburst is comparable to the beam size
  - M82 is not a point source nor an extended flat source for FTS bolometers
Source-beam coupling correction

- To compare the SED with models, we need to scale the spectrum to a single beam size with a source-beam coupling factor $\eta(\lambda)$
  - Largest beam size is 43.4"
- We assume Gaussian beams $[b(x,\text{FWHM}(\lambda))]$ and same light distribution $[f(x)]$ at all wavelengths $[\lambda]$
  - CO line maps are not so different from continuum emission distribution
- The source-beam coupling factor is given by:
  $$\eta(\lambda) = \frac{\int f(x)b(x,\text{FWHM}(\lambda))d\Omega}{\int f(x)b(x,43.4")d\Omega}$$
Source-beam coupling correction (2)

- The value of $\int f(x) b(x, \text{FWHM}(\lambda)) \, d\Omega$ was determined convolving M82 250µm maps with a gaussian beam $b'(x, \sqrt{\text{FWHM}^2 - 18.1''^2})$.

- Extended-source flux calibration (based on telescope modelling) is less noisy than point-source flux calibration but gives fluxes 2x fainter than photometry.
  - Known problem, under analysis.

- We had to multiply by another scaling factor to match photometry in the same beam.
M82 reconstructed apodized spectrum
Line extraction

- Emission line extraction from un-apodized spectrum with SLIDE tool
  - Remove continuum (graybody + polynomial)
  - Fit strongest line with sinc-convolved gaussian
  - Remove the fitted line and iterate on the residual

- Detected lines:
  - $^{12}$CO J=4-3 up to J=13-12
  - 3 $^{13}$CO lines (+1)
  - 1 HCN line
  - 2 [Cl] and [NII] lines

- Additional error ~30% (1σ) from corrections / calibration

<table>
<thead>
<tr>
<th>Transition name</th>
<th>Frequency (rest, GHz)</th>
<th>Flux ($10^3$ Jy km s$^{-1}$)</th>
<th>Flux ($10^{-16}$ W m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$CO J=4-3</td>
<td>461.041</td>
<td>74.1 ± 2.2</td>
<td>11.32 ± 0.33</td>
</tr>
<tr>
<td>$^{12}$CO J=5-4</td>
<td>576.268</td>
<td>80.9 ± 2.3</td>
<td>15.53 ± 0.45</td>
</tr>
<tr>
<td>$^{12}$CO J=6-5</td>
<td>691.473</td>
<td>74.0 ± 2.0</td>
<td>17.04 ± 0.46</td>
</tr>
<tr>
<td>$^{12}$CO J=7-6</td>
<td>806.652</td>
<td>77.7 ± 3.1</td>
<td>20.89 ± 0.84</td>
</tr>
<tr>
<td>$^{12}$CO J=8-7</td>
<td>921.800</td>
<td>60.7 ± 2.1</td>
<td>18.64 ± 0.65</td>
</tr>
<tr>
<td>$^{12}$CO J=9-8</td>
<td>1036.912</td>
<td>50.5 ± 2.3</td>
<td>17.44 ± 0.79</td>
</tr>
<tr>
<td>$^{12}$CO J=10-9</td>
<td>1151.985</td>
<td>32.6 ± 1.3</td>
<td>12.51 ± 0.50</td>
</tr>
<tr>
<td>$^{12}$CO J=11-10</td>
<td>1267.014</td>
<td>21.9 ± 1.5</td>
<td>9.28 ± 0.63</td>
</tr>
<tr>
<td>$^{12}$CO J=12-11</td>
<td>1381.995</td>
<td>14.0 ± 1.2</td>
<td>6.44 ± 0.57</td>
</tr>
<tr>
<td>$^{12}$CO J=13-12</td>
<td>1496.922</td>
<td>7.1 ± 0.9</td>
<td>3.53 ± 0.93</td>
</tr>
<tr>
<td>$^{13}$CO J=5-4</td>
<td>550.926</td>
<td>5.3 ± 0.7</td>
<td>0.98 ± 0.12</td>
</tr>
<tr>
<td>$^{13}$CO J=6-5</td>
<td>531.716</td>
<td>2.9 ± 0.7</td>
<td>0.52 ± 0.12</td>
</tr>
<tr>
<td>$^{13}$CO J=7-6</td>
<td>771.184</td>
<td>3.2 ± 0.6</td>
<td>0.81 ± 0.16</td>
</tr>
<tr>
<td>$^{13}$CO J=8-7</td>
<td>881.273</td>
<td>2.3 ± 0.7</td>
<td>0.68 ± 0.22</td>
</tr>
<tr>
<td>HCN J=6-5</td>
<td>531.716</td>
<td>2.9 ± 0.7</td>
<td>0.52 ± 0.12</td>
</tr>
<tr>
<td>[Cl] $^3P_1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table><p>ightarrow ^3P_0$ | 492.161 | 20.6 ± 1.6 | 3.38 ± 0.26 |
| [Cl] $^3P_2ightarrow ^3P_1$ | 809.342 | 43.2 ± 0.9 | 11.66 ± 0.25 |
| [NII] $^3P_1ightarrow ^3P_0$ | 1462.000 | 124.1 ± 5.8 | 60.51 ± 2.85 |</p>
M82 $^{12}\text{CO}$ SLED

- The Spectral Line Emission Distribution (SLED) of $^{12}\text{CO}$ peaks at J=7-6
- Low J lines taken from Ward et al (2003) in a similar area
- Only with Herschel we can determine the peak of the SLED

![Graph showing the relationship between $E_u/k$ (K) and $J$ with data points from This Work and Ward et al. (2003).]
RADEX modelling

- We used RADEX (van det Tak et al 2007) non-LTE code to compute $^{12}$CO and $^{13}$CO lines for a large parameter grid
  - $T_{\text{kin}}$: 20-1000K; $n_{\text{H}_2}$: 100-10$^6$cm$^{-3}$; $N(^{12}\text{CO})$: 10$^{15}$-10$^{18}$cm$^{-2}$; $N(^{13}\text{CO})$: 10$^{13}$-10$^{17}$cm$^{-2}$
- We computed the likelihood of each model
  - A single component was assumed
  - Had to add 20% uncertainty for lines in SLW and 10% in lines in SSW range
Modelled $^{12}$CO SLED

- SPIRE-detected CO lines well reproduced by a warm ($T_{\text{kin}} = 545$ K) molecular gas component with mass $1.2 \times 10^7$ Msun
- Same temperature of H2 S(1) – S(2) MIR lines

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Most Probable Value</th>
<th>range $^\dagger$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{kin}}$ (K)</td>
<td>545</td>
<td>350 – 825</td>
</tr>
<tr>
<td>$\log_{10} n(H_2)$ (cm$^{-3}$)</td>
<td>3.7</td>
<td>3.0 – 4.1</td>
</tr>
<tr>
<td>$\log_{10} N^{(12}{\text{CO}})$ (cm$^{-2}$)</td>
<td>19.0</td>
<td>18.5 – 19.8</td>
</tr>
<tr>
<td>$\log_{10} \Phi_A N^{(12}{\text{CO}})$ (cm$^{-2}$)</td>
<td>17.4</td>
<td>17.2 – 17.9</td>
</tr>
<tr>
<td>$N^{(12}{\text{CO}})/N^{(13}{\text{CO}})$</td>
<td>20</td>
<td>15 – 37</td>
</tr>
<tr>
<td>$\log_{10} P$ (K cm$^{-3}$)</td>
<td>6.4</td>
<td>5.8 – 6.7</td>
</tr>
<tr>
<td>$M_{\text{gas}}$ (x$10^7$ M$\odot$)</td>
<td>1.2</td>
<td>0.7 – 3.6</td>
</tr>
</tbody>
</table>
SPIRE + ground-based SLED

- Low J lines dominated by cold gas, as determined by various ground-based works
- The sum of 2 components (cold at ~25K, warm at ~550K) reproduce well the entire SLED (SPIRE + ground data)
- Mass of cold gas is ~3 times the mass of warm gas
  - Warm and cold components have similar pressure
Heating and cooling mechanisms

- At ~500K MIR H$_2$ rotational lines are the dominant coolant
  - CO luminosity ~ 5 x 10$^6$ L$_{\odot}$
  - H$_2$ luminosity ~ 3 x 10$^7$ L$_{\odot}$ (Beirão et al. 2008)
  - [CI] lines (491+809 GHz) ~ 5.4 x 10$^5$ L$_{\odot}$

- We considered several heating mechanisms as responsible for the warm molecular gas:
  - UV powered PDRs: observed CO lines too luminous compared with PDR models; would need too high density
  - X-ray powered XDRs: X-ray luminosity too low, and SLED decreases at high J (contrary to XDR-dominate Mkr231 in Loenen talk)
  - Cosmic ray: would need > 10 times CR rate of MW
  - Dissipation of turbulence (Falgarone & Puget 1995, Pan & Padoan 2009): from velocity gradient from RADEX (~35km/s/pc), turbulence can match the observed cooling
Conclusions

• We have presented the Herschel-SPIRE spectroscopic observations of the starburst galaxy M82.
• We derived a source-beam coupling correction to scale the observed spectrum to a single beam.
• Prominent CO ladder along with [C I] and [N II] lines.
• Modelling of CO lines clearly indicates the presence of a warm gas component at ~550K in addition to the cold (~25K) component found by ground-based studies.
• The temperature and mass of warm gas are in agreement with the H$_2$ rotational lines observations from Spitzer and ISO.
• H$_2$ is the dominant coolant instead of CO.
• Turbulence generated by stellar winds and supernovae may be the dominant heating mechanism.