How warm is the molecular gas in active environments?

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The cycle of interstellar matter in the Milky Way, stars form out of collapsing clouds of cold, dense molecular gas. 

~63% H₂
~36% He
~1% other molecules + dust

is that true for all galaxies?
Starbursts: just scaled-up star formation?

- M82 (NASA, ESA, The Hubble Heritage Team) (Thompson et al. 2006)
- non-standard conversion $I_{\text{CO}(1-0)} \rightarrow N_{\text{H}_2}$
- non-standard initial mass function? (Klessen et al. 2007 + obs.)
- evidence for warm molecular gas (e.g. Mauersberger et al. 2003)
Emission from molecular gas clouds

The fundamental dilemma: Photon trapping

- Molecular excitation

\[ n_i \sum_{j=1}^{k} A_{ij} + B_{ij} u_{ij} + C_{ij} = \sum_{j=1}^{k} n_j (B_{ji} u_{ji} + C_{ji}) \]

- Radiative transfer

\[ \frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu \]

⇒ make a (simple) model, e.g.

large velocity gradient (LVG) model: \( T_{\text{kin}}, n_{\text{H}_2}, abu_{\text{mol}}/\text{grad}(v) \)
Why formaldehyde ($\text{H}_2\text{CO}$)?

- many gas tracers suffer from a $T$-$n$ degeneracy

measured line ratios:

$\text{CO}(2-1)/\text{CO}(1-0) = 0.9$

$\text{CO}(3-2)/\text{CO}(2-1) = 0.7$

$\text{CO}(3-2)/\text{CO}(1-0) = 0.6$

$^{12}\text{CO}(1-0)/^{13}\text{CO}(1-0)$
Why formaldehyde (H$_2$CO)?

- H$_2$CO is sensitive to temperature \textit{and} density.
  many gas tracers suffer from a T-n degeneracy.
Why formaldehyde (H$_2$CO)?

- H$_2$CO is sensitive to temperature *and* density. Many gas tracers suffer from a T-n degeneracy.
- H$_2$CO has a rich spectrum.

![Diagram of H$_2$CO energy levels](image)
Why formaldehyde (H$_2$CO)?

- H$_2$CO is sensitive to temperature and density. Many gas tracers suffer from a T-n degeneracy.
- H$_2$CO has a rich spectrum. Multiple lines in the same bandpass avoids:
  - calibration issues
  - different beam widths
  - pointing uncertainties
- Limited line blending.

H$_2$CO lines at 218GHz
Why formaldehyde ($\text{H}_2\text{CO}$)?

- $\text{H}_2\text{CO}$ is sensitive to temperature \textit{and} density
  - many gas tracers suffer from a T-n degeneracy
- $\text{H}_2\text{CO}$ has a rich spectrum
  - multiple lines in the same bandpass avoids
    - calibration issues
    - different beam widths
    - pointing uncertainties
- limited line blending
- constant abundance in a variety of environments
  - $[\text{H}_2\text{CO}]/[\text{H}_2] \sim 10^{-10}$ in MW
  - (e.g. Johnstone et al. 2003)
Why formaldehyde (H$_2$CO)?

- H$_2$CO is sensitive to temperature and density.

The Galactic thermometer: NH$_3$

\[
\frac{[\text{NH}_3]}{[\text{H}_2]} \sim 10^{-5} \ldots 10^{-8} \text{ in MW}
\]

M82: $T_{\text{rot}} \sim 29$ K?

(Mauersberger et al. 2003)
Selected $\text{H}_2\text{CO}$ transitions

- $3_{03}-2_{02}$ (218.2 GHz)
- $3_{22}-2_{21}$ (218.5 GHz)
- $3_{21}-2_{20}$ (218.8 GHz)
- $2_{02}-1_{01}$ (145.6 GHz)
H$_2$CO at 218 GHz: dependent lines

H$_2$CO\( (3_{03}-2_{02}) \)
H$_2$CO\( (3_{22}-2_{21}) \)
H$_2$CO\( (3_{21}-2_{20}) \)

v = 132 km/s, w = 111 km/s
H$_2$CO at 146 GHz: blended lines

- H$_2$CO(2$_{02}$-1$_{01}$)
- HC$_3$N(16-15)

$\nu = 132$ km/s
$w = 111$ km/s

<table>
<thead>
<tr>
<th></th>
<th>$3_{21}$-2$_{20}$</th>
<th>$3_{22}$-2$_{21}$</th>
<th>$3_{03}$-2$_{02}$</th>
<th>2$<em>{02}$-1$</em>{01}$</th>
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<tbody>
<tr>
<td>$\nu_0$ (GHz)</td>
<td>218.76</td>
<td>218.48</td>
<td>218.22</td>
<td>145.60</td>
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<tr>
<td>Int. (K km/s)</td>
<td>0.53(0.14)</td>
<td>1.09(0.15)</td>
<td>2.09(0.16)</td>
<td>2.76(0.10)</td>
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</table>
From data to properties: LVG analysis

\[ \frac{N(\text{H}_2\text{CO}(3_{03}-2_{02}))/\Delta v}{N(\text{H}_2\text{CO}(3_{03}-2_{02}))} = \frac{N(\text{H}_2\text{CO}(3_{03}-2_{02}))/\Delta v}{N(\text{H}_2\text{CO}(3_{03}-2_{02}))} \]

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\[ \Rightarrow T_{\text{kin}}, n_{\text{H}_2}, N_{\text{H}_2\text{CO}}/\Delta v \text{ or } X_{\text{H}_2\text{CO}}/\text{grad}v, M_{\text{mol}} \ldots \]
First results: M82

- prototype of a starburst galaxy
- high IR luminosity
- galactic wind
- dense molecular gas concentrated towards the centre
- an “evolved” starburst?

(NASA, ESA, The Hubble Heritage Team)

(Weiss et al. 2001)
First results: M82

**NE**

218 GHz

<table>
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<th>Velocity (km/s)</th>
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<tr>
<td>T_{mb} (mK)</td>
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**SW**

218 GHz

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**146 GHz**

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</table>
First results: M82

\[ \frac{H_2CO(3_{03}-2_{02})}{H_2CO(3_{21}-2_{20})} \quad \frac{H_2CO(2_{02}-1_{01})}{H_2CO(3_{03}-2_{02})} \quad \frac{H_2CO(2_{02}-1_{01})}{H_2CO(3_{21}-2_{20})} \]

\[ T_{\text{kin}} \sim 191 \text{ K (NE)} / 209 \text{ K (SW)} \quad n_{H_2} \sim 7 \times 10^3 \text{ cm}^{-3} \]

\[ N_{H_2CO}/\Delta v \sim 2 \times 10^{13} \text{ cm}^{-2}/\text{km s}^{-1} \quad M_{\text{mol}} \sim 1.4/1.7 \times 10^8 M_{\odot} \]

\[ X_{H_2CO}/\text{grad}v \sim 1 \times 10^{-9} \text{ km}^{-1} \text{ s pc} \]

(Muehle et al. 2007)
First results: NGC 253

- nearby starburst galaxy
- high IR luminosity
- galactic wind
- molecular gas in circum-nuclear disk
- chemical abundances differ from those of M82 ⇒ a younger “twin” of M82?

(Sakamoto et al. 2006)
First results: NGC 253

To be published soon …
A kinetic temperature of $\sim 150$ K?

- Multi-transition NH$_3$ and CS (Mauersberger et al. 2003):
  $T_{\text{rot}} \sim 50$ K + $> 150$ K in other starburst galaxies (except M82)

- IR quadrupole H$_2$ transitions (Rigopoulou et al. 2002):
  $T_{\text{kin}} \sim 150$ K in starburst and Seyfert galaxies

- Multi-transition CO, HCN, HCO$^+$ in SB (Greve et al. 2009):
  $T_{\text{kin}} \sim 60...120$ K, $n_{\text{H}_2} \sim 10^4...6$ cm$^{-3}$ (warm component)

- Multi-transition CO in M82 (Mao et al. 2000):
  $T_{\text{kin}} \sim 60...130$ K, $n_{\text{H}_2} \sim 10^{3.3...3.9}$ cm$^{-3}$ (high-excitation lines)

- Multi-transition CO in M82 (Ward et al. 2003):
  $T_{\text{kin}} \sim 14$ K, $n_{\text{H}_2} \sim 10^{3.5}$ cm$^{-3}$
  $T_{\text{kin}} \sim 170$ K, $n_{\text{H}_2} \sim 10^{2.9}$ cm$^{-3}$ (median values)

- High-resolution NH$_3$ in NGC 253 (Ott et al. 2005):
  $T_{\text{kin}} \sim 150...260$ K
Conclusions

- selected H$_2$CO lines powerful diagnostics for starburst galaxies: $T_{\text{kin}}, n_{\text{H}_2}, N_{\text{H}_2\text{CO}}/\Delta v$
- detection of para-H$_2$CO lines up to $K_a=2$
  (M82, NGC 253)

First results:
- circumnuclear ring in M82:
  $T_{\text{kin}} \sim 200 \text{ K}, n_{\text{H}_2} \sim 7 \times 10^3 \text{ cm}^{-3}, M_{\text{mol}} \sim 3 \times 10^8 \text{ M}_{\text{sun}}$
- circumnuclear disk of NGC 253 (prelim. results):
  $T_{\text{kin}} \sim 150 \text{ K}, n_{\text{H}_2} \sim 10^4 \text{ cm}^{-3}$
Open questions

- Which classes of active galaxies exhibit a warm gas phase?
- How extended is the warm phase?
- Relation warm gas/cold gas?
- Correlation with star formation rate, gas content, age of starburst, AGN activity, …
Outlook

**ALMA:**
- p-\(\text{H}_2\text{CO}\) lines readily detectable
- maps give source sizes, distribution, etc.

**e-MERLIN:**
- maps of o-\(\text{H}_2\text{CO}\) line at 6 cm
  - o/p ratio, formation temp.
- ammonia lines at 24 GHz
Starbursts:
just scaled-up star formation?

- non-standard conversion $I_{\text{CO}(1-0)} \rightarrow N_{\text{H}_2}$
- non-standard initial mass function? (Klessen et al. 2007 + obs.)
- evidence for warm molecular gas (e.g. Mauersberger et al. 2003)

Caution, gas may be hot!