Absorption spectroscopy with Herschel/HIFI and IRAM-PdBI: Promises for ALMA

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Why Absorption Spectroscopy?

- Sensitivity limited to continuum sensitivity, access to weak features
- Background sources: from stars/star forming regions to QSOs/distant galaxies
- Direct probe of line opacity => easier analysis of molecule column density
- Comparison over a broad spectral range if the background source structure is understood (eg from cm to IR for star forming regions)
- Less information on spatial structure => need for extended continuum sources.
Molecules detected by absorption spectroscopy

- First detections: CH, CN, CH\(^+\) (1937 - 1940)
- UV / Visible/IR absorption
  - H, H\(_2\), C\(^+\), C, CO, CH, C\(_2\), C\(_3\), CN, OH, NH, H\(_3\)^+...
  - relatively simple molecules + atoms/ions (Na, Ca...)
  - DIBs ..., PAH?

- Radio absorption:
  - HI, OH, CO, CN, H\(_2\)O, H\(_2\)S, HCO\(^+\), CCH, HCN, HNC, CS, NH\(_3\), H\(_2\)CO, c-C\(_3\)H\(_2\), ...
  - From simple to ~ complex species
  - Little overlap between radio and visible spectral domains
  - Potential tracers of H\(_2\), cosmic ray ionization rate, dissipation of turbulence...
$\text{HCN/HCO}^+ \sim 1.3 \quad \text{HNC/HCO}^+ \sim 0.4 \quad \text{CN/HCO}^+ \sim 11.2$

$\text{HCN/HNC \sim 4.7, CN/HNC \sim 22.7 \quad \text{CCH/c-C}_3\text{H}_2 \sim 28}$

Similar properties as the diffuse matter probed towards high latitude sources (Liszt, Lucas et al.)
Molecules in the diffuse ISM (Liszt, Lucas, Pety)

Lower or Comparable abundances in diffuse and dense gas

HCO$^+$ & CCH (c-$C_3H_2$ ?) tracers of $H_2$ in diffuse gas (ubiquitous absorption)

Table 3. Relative abundances $10^8 \times N(\text{species})/N(H_2)$.

<table>
<thead>
<tr>
<th>Species</th>
<th>$\zeta$ Oph$^1$</th>
<th>Our Work$^2$</th>
<th>TMC-1$^3$</th>
<th>BD-G$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH</td>
<td>10</td>
<td>10</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>CO</td>
<td>480</td>
<td>300</td>
<td>8000</td>
<td>41</td>
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<tr>
<td>HCO$^+$</td>
<td>0.2-0.3</td>
<td>0.8</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>C$^+$</td>
<td>26 100</td>
<td></td>
<td>89 100</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>700</td>
<td></td>
<td>720</td>
<td></td>
</tr>
<tr>
<td>C$_2$</td>
<td>3.3</td>
<td></td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>C$_3$</td>
<td>0.35</td>
<td></td>
<td>$10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td>5.4</td>
<td>2</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>CH$^+$</td>
<td>6.3</td>
<td></td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>C$_2$H</td>
<td></td>
<td>2.9</td>
<td>5-10</td>
<td>0.4</td>
</tr>
<tr>
<td>C$_3$H$_2$</td>
<td>0.14</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>CN</td>
<td>0.54</td>
<td>2.0</td>
<td>3</td>
<td>0.30</td>
</tr>
<tr>
<td>HCN</td>
<td>(0.079)</td>
<td>0.30</td>
<td>2</td>
<td>0.007</td>
</tr>
<tr>
<td>HNC</td>
<td>(0.016)</td>
<td>0.06</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td></td>
<td>0.25</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>SO</td>
<td>0.15</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$CO</td>
<td>0.40</td>
<td>2</td>
<td></td>
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<tr>
<td>NH</td>
<td>0.19</td>
<td></td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>NH$_3$</td>
<td></td>
<td>0.20</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
PRISMAS programme: Absorption spectroscopy

- Hydride ground state lines in the submm spectral range
- Excellent sensitivity: reach the same range of column density as visible spectroscopy for molecules in common (e.g., CH and CH\(^+\)) => probe diffuse and translucent gas with Av few mag in the FIR spectral range.
- 8 sources, 25 Species
  - C: CH, \(^{13}\)CH, CH\(^+\), \(^{13}\)CH\(^+\), CH\(_2\)C\(_3\)
  - N: NH, NH\(_2\), NH\(_3\) (o & p), \(^{15}\)NH\(_3\), ND, NH\(_2\)D, NH\(^+\)
  - O: OH\(^+\), H\(_2\)O\(^+\) (o & p), H\(_3\)O\(^+\), H\(_2\)O (o & p), H\(_2\)\(^{18}\)O, HDO, D\(_2\)O
  - F: HF, DF
  - Cl: HCl, HCl\(^+\)
  - S: SH\(^+\)
Hydrides

- built in the first chemical steps starting from atomic gas
- at the root of interstellar chemistry
- Diagnostics of physical / chemical processes

Godard et al.
2009
Molecular hydrogen tracers

Visible/UV spectra

CH scales with $H_2$ ($CH/H_2 \sim 3.5 \times 10^{-8}$)

Sheffer et al 2008
New tracers of $\text{H}_2$ in the submillimeter: Hydrogen fluoride (HF) & CH

- Fluorine reacts with $\text{H}_2$, making HF
- (Neufeld et al)
- $\Rightarrow$ HF uses all the gas phase F
- $\Rightarrow$ HF reveals $\text{H}_2$
- $\Rightarrow$ HF is present as soon as $\text{H}_2$ is present, even in clouds with no detectable CO or $\text{H}_2\text{O}$.
- $\Rightarrow \tau(\text{HF}) > \tau(\text{p-H}_2\text{O})$
- $\Rightarrow \tau(\text{HF}) \sim N(\text{H}_2)/10^{20}\text{cm}^{-2}$
  $ (dv = 1 \text{ km/s} $)

Neufeld et al 2010a A&A 518
Sonnentrucker et al, and poster
- $\text{HF}/\text{H}_2 \sim 1 - 3 \times 10^{-8}$ ($\text{F}/\text{H}=1.8 \times 10^{-8}$)

- $N(\text{HF}) : 1 - 70 \times 10^{12} \text{ cm}^{-2}$

Sonnentrucker, Neufeld et al (A&A 521)
• CH ground state triplet at 532 & 536 GHz.
• Lines not saturated but complex profiles
• Combination of emission & absorption
• $N(\text{CH}) \sim \text{few } 10^{14}$ cm$^{-2}$
• CH & HF consistent with $\text{CH}/\text{H}_2 \sim 3.5 \times 10^{-8}$ derived from UV/visible
• $\tau(\text{CH}) \sim N(\text{H}_2)/10^{21}$ cm$^{-2}$

Gerin et al 2010  A&A 521
CH: relation with other molecules:
linear scaling $\Rightarrow$ constant abundance ratio
• Well defined trends & deviations in narrow velocity intervals

• $\text{CCH/CH} \sim 0.6 - 1.2$

• $\text{CN/CH} \sim 0.5 - 1$

• $\text{HCO}^+/\text{CH} \sim 0.04 - 0.08$

• Gerin et al A&A 521
Cosmic rays ionization rate

Different models for the propagation of cosmic rays and for their energy spectrum. ζ is expected to decrease with increasing column density of matter. Local variations?

Padovani et al (2009)
Oxygen hydrides: $\text{OH}^+$, $\text{H}_2\text{O}^+$, $\text{H}_3\text{O}^+$

- $\text{o-}\text{H}_2\text{O}^+$ at 1.115 THz => Strong absorption in diffuse ISM and in outflows associated with massive YSO
- $\text{p-}\text{H}_2\text{O}^+$: weaker lines 607, 633 GHz

Gerin et al, Neufeld et al, Ossenkopf et al, Wyrowski et al, Benz et al ...
OH$^+$ 971 GHz
(also 909, 1033 GHz)
• OH$^+$ and H$_2$O$^+$ are not well correlated with CH.

• OH$^+$ and H$_2$O$^+$ trace a phase with a small fraction of H in H$_2$.
**Oxygen hydrides**: $\text{OH}^+, \text{H}_2\text{O}^+, \text{H}_3\text{O}^+$

- $\text{OH}^+/\text{H}_2\text{O}^+ > 4$

- $\Rightarrow \text{OH}^+$ mostly in atomic gas with a small fraction of $\text{H}_2$ ($< 10\%$)

$\Rightarrow$ Analytic expression

$$n(\text{OH}^+)/n(\text{H}_2\text{O}^+) = 0.64 + 0.12 \cdot (T/300\text{K})^{-0.5}/f(\text{H}_2)$$

$\text{OH}^+/\text{H} \sim 3 \times 10^{-8}$  \quad $\text{H}_2\text{O}^+/\text{H} \sim 3 \times 10^{-9}$

$\text{O}^+$ formed by charge transfer between $\text{O}$ and $\text{H}^+$

$\Rightarrow \text{OH}^+$ & $\text{H}_2\text{O}^+$ sensitive to $\zeta$, the ionization rate due to cosmic rays \quad $\zeta(\text{H}) = 0.6 - 2.4 \times 10^{-16} \text{ s}^{-1}$
Comparison with $H_3^+$

$H_3^+$ absorption from diffuse gas

High ionization rate $\zeta > 10^{-16}$ s$^{-1}$

(Indriolo et al 2007, 2009)
CH⁺: a probe of energetic events
dissipation of turbulence

Godard et al 2009, 2010
• CH$^+$ shows strong absorption, reaching saturation

• use $^{13}$CH$^+$

• Agreement with $^{13}$CH$^+$ data from CSO (Falgarone in prep).

• Absorption with no CH, no HCO$^+$ counterpart

• $N$(CH$^+$) $>$ 3 x $10^{14}$ cm$^{-2}$
**SH\textsuperscript{+} another tracer of the dissipation of turbulence!**

- Detection in the SgrB2 l.o.s with APEX (Menten et al)
- SH\textsuperscript{+} produced by the reaction S\textsuperscript{+} + H\textsubscript{2} that has E > 4000K
- CH\textsuperscript{+} & SH\textsuperscript{+} complementary diagnostics

*Godard, Falgarone in preparation*
ISM Structure : IRAM-PdBI observations

- Set-up with HCO$^+$, H$^{13}$CO$^+$, CCH, HCN, SiO & HCO simultaneously, 40 kHz.
- W51, conf D, 2 field mosaic: ~5" beam.
Velocity structure

3 velocity components at 5, 6 & 13 km/s

Similar profiles over the mapped area

Comparison with ≠ beams ~ OK
High sensitivity => weak lines
Perspectives for ALMA: local universe

- Imaging of background sources => spatial structure, down to small scales
- Systematic surveys of background sources => characterization of the diffuse ISM (mass, H2 content, energetics, dynamics)
- Very weak lines/Isotopologues
  1/ abundance gradients and metallicity
  2/ test of chemical routes: eg origin of CCH by comparison of C13CH and 13CCH? (asymmetry in TMC1 - Sakai et al.)
Perspectives for ALMA: distant universe

• Molecular lines offer sensitive probes of ISM content: gas mass, gas density, energetics, ionization rate, ionization fraction, etc.
• Molecule excitation $\rightarrow$ CMB if diffuse gas

• new spectral lines $\Rightarrow$ new possibilities of testing possible drifts of fundamental constants
  (eg comparison of NH3 rotational and inversion lines is sensitive to me/mp Henkel et al 2010)
Interesting lines for absorption

\[ Z = 0 \]

Hydrides: \( \text{H}_2\text{S}, \text{p-NH}_2, \text{p-H}_2\text{O}^+, \text{HCl}, \text{SH}^+, 13\text{CH}^+, \text{HDO}, \text{OH}^+ \)

Other interesting absorption

\( \text{HCO}^+, \text{HOC}^+, \text{CN}, \text{CCH}, \text{c-C}_3\text{H}_2, \text{HCN}, \text{HNC}, \text{H}_2\text{CO}, \text{CS}, \text{SO}, \text{etc} \)

High redshift (\( z > 0.4 \))

More hydride lines: \( \text{CH}, \text{H}_2\text{O}, \text{NH}_3, \text{HCl}, \text{CH}^+, \text{NH}, \text{NH}_2, \text{OH}^+, \text{H}_2\text{O}^+, \text{H}_3\text{O}^+, \text{HF} \)