Ground and Airborne observations of interstellar Hydrides: New Results from APEX and SOFIA

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Outline

• Hydrides and the Herschel legacy
• APEX observations of Hydrides: \( \text{OH}^+, \text{SH}^+, \text{NH}_2 \)
• SOFIA observations of Hydrides: \( \text{OH, SH, NH}_3 \)
• Hydrides at high-redshifts
Hydrides

• First molecules detected in ISM:
  – optical absorption lines from CH and CH$^+$ in stellar spectra (Dunham 1937)
  – absorption is due to intervening interstellar diffuse clouds on the lines-of-sight

• Key ingredients of interstellar chemistry
  – initial products of chemical networks that form more complex molecules
  – Fundamental rotational transitions in submm range
The Herschel Legacy

- Two large, dedicated key programs:
  - **PRISMAS** (PI: Maryvonne Gerin), diffuse clouds absorption studies
  - **WISH** (PI: Ewine van Dishoeck), water in star forming regions
- O-bearing: $\text{H}_2\text{O}$, $\text{H}_n\text{O}^+$
- C-bearing: $\text{CH}$, $\text{CH}^+$
- N-bearing: $\text{NH}$, $\text{NH}_2$, $\text{NH}_3$
- Others: $\text{SH}^+$, $\text{ArH}^+$
The Herschel/HIFI Legacy

- Hydrides abundant component of ISM, in particular diffuse clouds, observations reveal chemical composition
- Some rather associated with molecular phase, other with atomic phase
- Probes of physical conditions, e.g. cosmic ray ionization (Neufeld+2010)

- Some key molecules have been missing: e.g. OH, H$_2$D$^+$, SH
Absorption studies

- Line optical depths from line-to-continuum ratio
- Hydrides have high critical densities: in diffuse clouds most molecules in ground state: → easy estimate of column density
- Columns measured as function of velocity, hence location on line-of-sights
APEX in a nutshell

- **12m**, modified copy of ALMA prototype ant.
- At **5100m** on Chajnantor Plateau (ALMA site)
- **MPG/ESO/OSO & Chile**
- Base in Sequitor @ 2500m with control room etc.
- Surface ~ **15 micron**
- Wobbling secondary
- BEs: many FFTSs
- FEs:
  - Heterodyne Rxs: 230-1500GHz
  - Bolometer arrays
Fig. 1. Zenith transmission of the atmosphere above Llano de Chajnantor at submillimeter wavelengths. Using data from the ALMA site characterization database covering the years 1995 to 2004, we calculate that the median column of precipitable water is about 1.2 mm and the 25% quartile about 0.7 mm, including data taken during the Bolivian winters. During the winter months the median drops by a factor 2-3. The project plan requires that all atmospheric windows accessible from ground shall be covered by state-of-the-art instruments. We superimpose the frequency coverage of the APEX facility and PI receivers, as they are in operation now (solid lines) and as committed for delivery (dotted). Several contributions to this special issue are dedicated to our instruments.
First detection of OH$^+$ with APEX: 909GHz rotational ground state line toward Sgrb2M

Wyrowski et al.: Interstellar OH$^+$

- Key ingredient of interstellar chemistry
- $\rightarrow$ initiating oxygen chemistry
- Very abundant!

$$
\begin{align*}
H & \xleftarrow{CR} \xrightarrow{H^+} O \xrightarrow{H_2} OH^+ \xrightarrow{H_2} H_2O^+ \xrightarrow{H_2} H_3O^+
\end{align*}
$$
**SH**\(^+\) @ 683GHz
Menten+2011

- Combining with results from 3mm survey (Belloche+2013)
- In addition: 
  - \(^{13}\)CH\(^+\), HCl
- Neutral SH: see later discussion of SOFIA result
OH$^+$ towards strong ATLASGAL sources

Wyrowski et al. (in prep.)

- Study distribution using ATLASGAL MSF regions as background candles
- 2$^{nd}$ strongest OH$^+$ finestructure line @ 1033GHz with new MPIfR THz RX (Leinz+2010)
- Almeida+1990:

<table>
<thead>
<tr>
<th>$\nu$ (MHz)</th>
<th>$J'-J''$</th>
<th>$S_{J',J''}$</th>
<th>$g_2=2J+1$</th>
<th>$A \times 10^{-2}$ (s$^{-1}$)</th>
<th>$I \times 10^{-5}$ (cgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>909121.07</td>
<td>0 - 1</td>
<td>0.333</td>
<td>1</td>
<td>1.569</td>
<td>6.986</td>
</tr>
<tr>
<td>971811.77</td>
<td>2 - 1</td>
<td>1.667</td>
<td>5</td>
<td>1.917</td>
<td>9.124</td>
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<tr>
<td>1033078.37</td>
<td>1 - 0</td>
<td>1.000</td>
<td>3</td>
<td>2.302</td>
<td>11.647</td>
</tr>
</tbody>
</table>
22/22 sources detected! Strongest detections shown.
OH$^+$ @ 1033GHz

- Total column densities:
  - $N \sim 10^{14} - 5 \times 10^{15}$ cm$^{-2}$
- New absorber G10.47+0.03 as second strongest line-of-sight
- Results can now be combined with WISH & ATLASGAL water follow ups (+ $H_2O^+ \rightarrow$ cosmic ray ion. Rate, e.g. Neufeld+2010)
Galactic distribution

- All velocity components:
- $10^{13-14}\text{cm}^{-2}$
- $R_{\text{gal}}$ from $v_{\text{lsr}}$
- Gradient compared with Shaver+1983
Nitrogen Hydrides

- Nitrogen chemistry poorly understood
- Current models do not reproduce $\text{NH}/\text{NH}_2/\text{NH}_3$ ratios properly (Persson+2010/12)
- $\text{NH}$ observed with Herschel towards many sources
- $\text{NH}_2$ observable with APEX, some new detections already made
- For $\text{NH}_3$ SOFIA can be used, see later slide
New ground-based NH$_2$

- First detection: SgrB2 by van Dishoeck+1993
- Master thesis C. Gette: 15 new APEX detections of ground state line at 462GHz!
Prospects for ALMA: Hydride lines accessible from ground

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transition</th>
<th>Frequency (GHz)</th>
<th>Band</th>
<th>Reference/Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH⁺</td>
<td>1–0</td>
<td>909.1588</td>
<td>10</td>
<td>Wyrowski et al. [6]</td>
</tr>
<tr>
<td>SH⁺</td>
<td>1–0</td>
<td>683.4223</td>
<td>9</td>
<td>Menten et al. [5]</td>
</tr>
<tr>
<td>SH⁺</td>
<td>1–0</td>
<td>345.9298</td>
<td>7</td>
<td>close to CO</td>
</tr>
<tr>
<td>SH⁺</td>
<td>2–1</td>
<td>893.1338</td>
<td>10</td>
<td>Menten et al. [5]</td>
</tr>
<tr>
<td>¹³CH⁺</td>
<td>1–0</td>
<td>830.2161</td>
<td>10</td>
<td>Menten et al. [5]</td>
</tr>
<tr>
<td>HCl</td>
<td>1–0</td>
<td>625.9188</td>
<td>9</td>
<td>Menten et al. [5]</td>
</tr>
<tr>
<td>H₂Cl⁺</td>
<td>1–0</td>
<td>485.4208</td>
<td>8</td>
<td>Lis et al. [13]</td>
</tr>
<tr>
<td>H₂O⁺</td>
<td>3/2–1/2</td>
<td>604.6786</td>
<td>9</td>
<td>Schilke et al. [14]</td>
</tr>
<tr>
<td>H₂O⁺</td>
<td>3/2–3/2</td>
<td>607.2273</td>
<td>9</td>
<td>Schilke et al. [14]</td>
</tr>
<tr>
<td>H₂O⁺</td>
<td>1/2–1/2</td>
<td>631.7241</td>
<td>9</td>
<td>Schilke et al. [14]</td>
</tr>
<tr>
<td>H₂O⁺</td>
<td>1/2–3/2</td>
<td>634.2729</td>
<td>9</td>
<td>Schilke et al. [14]</td>
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<tr>
<td>NH</td>
<td>1–0</td>
<td>946.4758</td>
<td>10</td>
<td>Hily-Blant et al. [15]</td>
</tr>
<tr>
<td>NH₂</td>
<td>3/2–3/2</td>
<td>462.4335</td>
<td>8</td>
<td>van Dishoeck et al. [16]</td>
</tr>
</tbody>
</table>

+ H₂¹⁸O, some H₂¹⁶O lines
+ THz lines: OH⁺, NH⁺
GREAT @ SOFIA

- Early Science Instr.
- PI Güsten (MPIfR),
- Channels (2 sim.):
  - L1: ~1250-1520 GHz
  - L2: ~1810-1910 GHz
  - Ma ~ 2510 GHz (OH)
  - Mb ~ 2680 GHz (HD)
  - H ~ 4750 GHz (OI)
- Note: UPGREAT to come next year with arrays and larger frequency coverage!
SOFIA SH detection
Neufeld+2012

- SH ground state at 1383GHz in gap of HIFI between band 5+6
- Clear identification from lambda doubling
- Detected in W49 envelope as well as LOS diffuse cloud
- Enhanced in warm regions heated e.g. by shocks

Fig. 1. Spectrum of SH $^2\Pi_{3/2} J = 5/2 \leftarrow 3/2$ obtained by GREAT toward W49N. Note that because GREAT employs double sideband receivers, the complete absorption of radiation at a single frequency will reduce the measured antenna temperature to one-half the apparent continuum level. The lambda doubling and hyperfine splittings are indicated by the red bars for a component at an LSR velocity of 40 km s$^{-1}$. 
Ammonia@1.8THz
Wyrowski+2012

- 3 absorption line detections
- All redshifted with respect to $v_{\text{sys}}$
- $\tau \sim 1$

Table 2. Line parameters from Gaussian fits to the NH$_3$ lines. Nominal fit errors are given in brackets. In addition, the velocity of C$^{17}$O (3–2) lines observed with the APEX telescope are given.

<table>
<thead>
<tr>
<th>Source</th>
<th>$T_{\text{peak}}$ (K)</th>
<th>$\Delta v$ (km s$^{-1}$)</th>
<th>$v_{\text{NH}_3}^{\text{LSR}}$ (km s$^{-1}$)</th>
<th>$v_{\text{C}^{17}\text{O}}^{\text{LSR}}$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W43-MM1</td>
<td>-0.96 (0.22)</td>
<td>5.3 (0.8)</td>
<td>99.7 (0.4)</td>
<td>97.65 (0.06)</td>
</tr>
<tr>
<td>G31.41+0.31</td>
<td>-1.18 (0.29)</td>
<td>3.7 (0.8)</td>
<td>99.4 (0.4)</td>
<td>97.02 (0.04)</td>
</tr>
<tr>
<td>G34.26+0.15</td>
<td>-3.38 (0.56)</td>
<td>5.5 (0.6)</td>
<td>61.2 (0.3)</td>
<td>58.12 (0.03)</td>
</tr>
</tbody>
</table>

Fig. 2. NH$_3$ spectra of the observed sources. Results of Gaussian fits to the line are overlaid in green. The systemic velocities of the sources, determined using C$^{17}$O (3–2) are shown with dotted lines.
Infall Results

- 3 clear detections of Ammonia line-of-sight infall consistent with results from cm-absorption and/or blue-skewed emission profiles
- More direct probe of infall that can be extended to earlier stages of SF without cm background continuum and cases where other species are depleted
- Infall rates of $3-10 \times 10^{-3} \, M_\odot/yr$ (if spherical)
- Update: extended to more sources and earlier stages, all detections, further red-shifted absorption
- Constrains on Nitrogen chemistry by combination with APEX $\text{NH}_2$
Hydrides @ high redshift

- Mostly promising ALMA science, e.g.:
  - $\text{H}_2\text{O}$
  - $\text{H}_2\text{O}^+$
  - $\text{OH}^+$
  - $\text{CH}$
  - $\text{CH}^+$
  - $\text{HF}$

Weiss+2013, ALMA SPT sources, 3mm surveys
Summary

- APEX lead to first ground-based detections of $\text{OH}^+$ and $\text{SH}^+$ paving the way for Hydrides studies with ALMA in the post-Herschel era

- SOFIA successful in even higher frequency observations of Hydrides, e.g. OH and SH, complementing both APEX/ALMA and Herschel

  - $\rightarrow$ to reach almost complete molecular coverage of initial chemical pathways