Origin and excitation mechanisms of the warm CO, OH and CH\(^+\) in PDRs

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• Orion A: massive star formation
• Many previous studies (e.g. Parmar et al. 1991, Tielens et al., Walmsley et al. 2000, Allers et al. 2005): comparison to new tracers, like highly excited lines
• Prototypical PDR
  1) Bright: UV field $2.5 \times 10^4 \times$ the standard interstellar radiation field
  2) Near: $\sim 400$ pc
  3) Nearly edge-on geometry: chemical stratification

Excitation and structure of the Orion Bar?
Photodissociation regions (PDRs)

Hollenbach & Tielens, 1999

- Widespread phenomena
- One of the most chemically active structures in the Universe
- UV-illuminated dense structures
- Heating dominated by FUV photons
- Chemical stratification dominated by FUV photons
- Cooling dominated by $\text{C}^+$, $\text{O}^0$, $\text{H}_2$, CO...
Mapping the Orion Bar with Herschel

PACS observed lines:
- OH 84 & 119 µm
- CH$^+$ J=3-2 (120 µm)
- CO J=19-18 (137 µm)
- O$^0$ 63 & 145 µm
- C$^+$ 158 µm
- N$^+$ 122 µm

Spatial resolution 5” - 11”

SPIRE observed lines (SSW & SLW):
- $^{12}$CO (J=4-3 to J=13-12)
- $^{13}$CO (J=5-4 to J=13-12)
- C$^{18}$O (J=5-4 to J=13-12)
- CH$^+$ J=1-0
- C$^0$ 370 & 492 µm
- H$_2$O 269, 399, & 538 µm
- N$^+$ 205 µm

Spatial resolution 12” - 24”
Mapping the Orion Bar with Herschel

Parikka et al., in prep.

- First spatially resolved maps of these lines (PACS)
- Total area of 110” x 110”
- Spatial resolution of 6” to 9” (0.012 – 0.018 pc)
- Each map has a specific morphology dependent on the local conditions and processes
Origin of CH$^+$ and OH emission

- Similar properties:
  - $n_{\text{crit}} \sim 10^{10}$ cm$^{-3}$
  - $E_u \sim 250$ K

- Both have a formation route with H$_2$

- Similar threshold:
  - CH$^+$ endothermicity: $\sim 4300$ K
  - OH activation barrier: $\sim 4800$ K

- Good correlation with high-J CO
- Emission peaks in clumps
- Originate in warm and dense gas

Parikka et al. in prep.
Comparison with vibrationally excited H$_2$

- **CH$:**
  - CH$^+$ formation:
    \[ H_2 + C^+ \rightarrow H + CH^+ \]  
    (endothermicity: 4300 K)
  - H$_2$ ro-vibrational energy: to overcome energy threshold
  - Formation process of CH$^+$ depends on H$_2^*$

- **OH:**
  - OH formation:
    \[ H_2 + O \rightarrow H + OH \]
  - OH formation less dependent on H$_2^*$
CH$^+$ and OH formation via vibrationally excited H$_2$

- CH$^+$ fractional abundance highly dependent on H$_2$
- OH much less dependent: energy activation barrier exists even when H$_2$ is v=3 (Sultanov & Balakrishnan 2005)
- Nagy et al. 2013:
  - CH$^+$ with H$_2$ formation (PDR code)
  - Wide line width could be due to chemical pumping (also our HIFI CH$^+$ J=2-1)
Unexpected proplyd detection

- OH 84 μm emission coincides with proplyd 244-440
- OH detected in protoplanetary disks (Sturm et al., 2010)
- Expected the emission to be dominated by the Bar
- Confirmation with SOFIA: to separate the velocities of proplyd and surrounding nebula

Parikka et al. in prep.
First time observed dense structures in high-J CO lines

The clumps in H^{13}CN (Lis & Schilke, 2003), CS and high-J CO are the same (size 10”-20”, similar ang. res.)

High-J CO directly traces irradiated and dense structures

Link between the core and the edge of the dense clumps

Lee et al. 2013
Parikka et al. in prep.
High-J CO excitation

CO-ratio (19-18/12-11)

- Peaks in front of high-J CO, where UV not attenuated in PDR
- peaks along with PAHs that are sensitive to UV flux
- UV dominates:
  1) photoelectric heating
  2) $\text{H}_2$ pumping & formation
  3) (CO pumping)
- High-J CO not seen in other PDRs where UV field is weaker (NGC 7023, Köhler et al. 2014)
RADEX results

Temperature maps

Column density maps

Parikka et al. in prep.
RADEX results

- Fitted with hydrogen densities of $10^5$, $10^6$, and $10^7$ cm$^{-3}$
- Comparing length to previous studies (e.g. Jansen et al. 1995): $10^6$ cm$^{-3}$ most likely solution ($10^7$ cm$^{-3}$, Lee et al.)
- High thermal pressure $\sim 2 \times 10^8$ K cm$^{-3}$
- Similar to pressure derived with PDR code in Orion Bar (Joblin et al. In prep.) and in NGC 7023 (Köhler et al. 2014, thesis of Emeric Bron)

<table>
<thead>
<tr>
<th>$n_H$ [cm$^{-3}$]</th>
<th>$N_{CO}$ [$10^{18}$ cm$^{-2}$]</th>
<th>$T_g$ [K]</th>
<th>$\eta$</th>
<th>$P$ [K cm$^{-3}$]</th>
<th>$l$ [pc]</th>
<th>$l$ ['']</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^5$ red</td>
<td>10</td>
<td>230</td>
<td>0.3</td>
<td>$2.3 \times 10^7$</td>
<td>0.58</td>
<td>230</td>
</tr>
<tr>
<td>$10^6$ blue</td>
<td>4</td>
<td>160</td>
<td>0.4</td>
<td>$1.6 \times 10^8$</td>
<td>0.026</td>
<td>13</td>
</tr>
<tr>
<td>$10^7$ green</td>
<td>4</td>
<td>120</td>
<td>0.5</td>
<td>$1.2 \times 10^9$</td>
<td>0.003</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Summary: Orion Bar

- CH$^+$ and OH in the Orion Bar
  - Emission mostly from warm and dense gas
  - Trace dense and irradiated structures
  - CH$^+$ forms via vibrationally excited H$_2$
  - OH emission coincides with a proplyd
- CO in the Orion Bar
  - UV heating is the main route of high-J CO excitation
  - Orion Bar has high thermal pressure ($\sim 10^8$ K cm$^{-3}$)
SOFIA
Stratospheric Observatory for Infrared Astronomy

- Boeing 747SP (Special Performance)
- Operating altitude: 11-14km
- above 99.8 percent of the Earth’s atmospheric water vapor
- mainly from Palmdale/CA
- US/German project
- Primary Mirror: 2.7m
- 8 instruments (6 infrared, 2 optical)
GREAT

- German REceiver for Astronomy at Terahertz Frequencies
- IR Heterodyne Spectrometer
- Observing modes: Position switching, Beam switching, Raster mapping, On-the-fly mapping
- 60 - 200 µm (several windows)

<table>
<thead>
<tr>
<th>Channels</th>
<th>Frequency Range [THz]</th>
<th>$T_{\text{rec}}$ [K], DSB*</th>
<th>Astronomical Lines of Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frequency L1</td>
<td>1.25 – 1.39</td>
<td>600</td>
<td>CO(12-11), OD, SH, H$_2$D*, HCN, HCO$^+$</td>
</tr>
<tr>
<td></td>
<td>1.42 – 1.52</td>
<td>600</td>
<td>CO(13-12), [NII]</td>
</tr>
<tr>
<td>Low-frequency L2</td>
<td>1.80 – 1.90</td>
<td>700</td>
<td>NH$<em>3$(3-2), OH($^2\Sigma</em>{1/2}$), CO(16-15), [CII]</td>
</tr>
<tr>
<td>Mid-frequency Ma</td>
<td>2.49 – 2.56</td>
<td>1500</td>
<td>(18)OH($^2\Pi_{3/2}$)</td>
</tr>
<tr>
<td>Mid-frequency Mb</td>
<td>2.67 – 2.68</td>
<td>3100</td>
<td>HD(1-0)</td>
</tr>
<tr>
<td>High-frequency H</td>
<td>4.745</td>
<td>1000</td>
<td>[OI]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Backends: Fast Fourier Transform Spectrometers</th>
<th>Bandwidth [GHz]</th>
<th>Resolution [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFFTS</td>
<td>1.5</td>
<td>0.212</td>
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<tr>
<td>XFFTS</td>
<td>2.5</td>
<td>0.044</td>
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<tr>
<td>FFTS4G</td>
<td>4.0</td>
<td>0.244</td>
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</tbody>
</table>
upGREAT

- 1.9 THz multi-pixel high resolution spectrometer

Table 1. Main atomic and molecular transitions accessible to upGREAT/LFA

<table>
<thead>
<tr>
<th>Species</th>
<th>Rest Freq.</th>
<th>Transition</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH</td>
<td>1.834 THz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>1.841 THz</td>
<td>$J = 16 - 15$</td>
<td></td>
</tr>
<tr>
<td>CII</td>
<td>1.9005 THz</td>
<td>$J = 3/2 - 1/2$</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>1.955 THz</td>
<td>$J = 17 - 16$</td>
<td></td>
</tr>
<tr>
<td>HeH*</td>
<td>2.01 THz</td>
<td></td>
<td>undetected in the ISM</td>
</tr>
<tr>
<td>OI</td>
<td>2.06 THz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>2.07 THz</td>
<td>$J = 18 - 17$</td>
<td>barely doable</td>
</tr>
<tr>
<td>CO</td>
<td>2.19 THz</td>
<td>$J = 19 - 18$</td>
<td>blocked by atmosphere</td>
</tr>
<tr>
<td>CO</td>
<td>2.42 THz</td>
<td>$J = 20 - 21$</td>
<td>not tunable yet</td>
</tr>
<tr>
<td>NII</td>
<td>2.459 THz</td>
<td>$J = 2 - 1$</td>
<td>blocked by atmosphere</td>
</tr>
<tr>
<td>OH</td>
<td>2.49 THz</td>
<td></td>
<td>not tunable yet</td>
</tr>
<tr>
<td>OH</td>
<td>2.51 THz</td>
<td></td>
<td>not tunable yet</td>
</tr>
<tr>
<td>CO</td>
<td>2.52 THz</td>
<td>$J = 21 - 20$</td>
<td>not tunable yet</td>
</tr>
</tbody>
</table>

Fig. 7. Sketch of the array-OTF mapping mode. Circles indicate the beam sizes in the hexagonal array pattern. The beam spacing is 33".

Risacher et al., in prep.
Horsehead mapped in C⁺

- 17.5′ x 12.5′
- spectral resolution: 0.19 kms⁻¹
- observed in 4h (vrt. Herschel/HIFI: 200h)
- Available at the SOFIA website