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

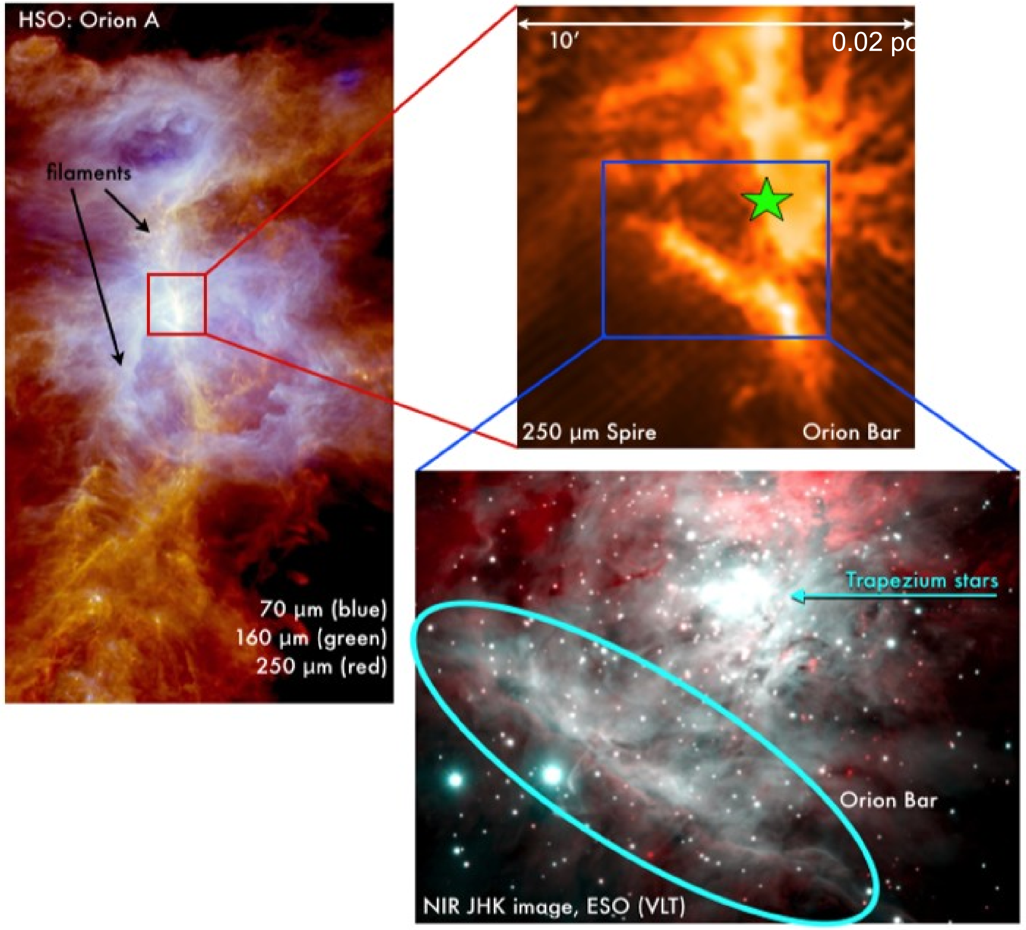
Anna Parikka

I. Physikalisches institut, Köln

In collaboration with E. Habart, J. Bernard-Salas, M. Köhler, J. R. Goicoechea, P. Pilleri, A. Abergel, C. Pinto, C. Joblin, M. Gerin, E. Dartois, B. Godard, D. Teyssier, O. Berné, A. Fuente

Orion Bar

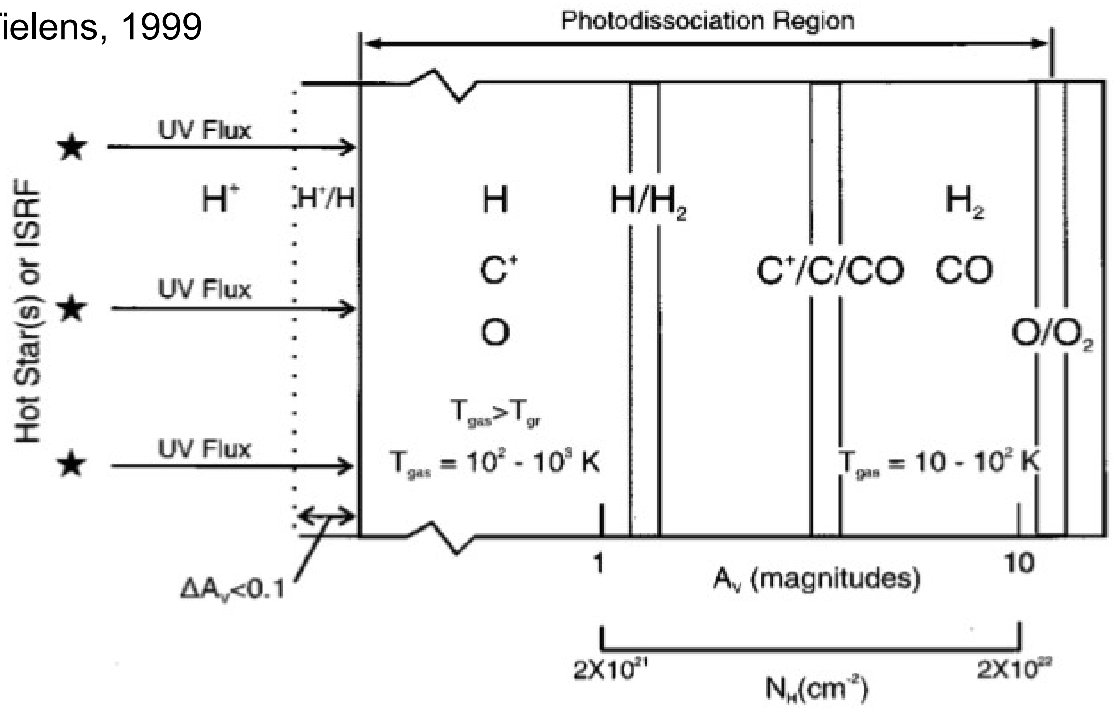
- Orion A: massive star formation
- Many previous studies (e.g. Parmar et al. 1991, Tielens et al., Walmsley et al. 2000, Allers et al. 2005): comparison to new tracers, like highly excited lines
- Prototypical PDR
  1) Bright: UV field 2.5×10^4 x the standard interstellar radiation field
  2) Near: ~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 C^+, O^0, 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”

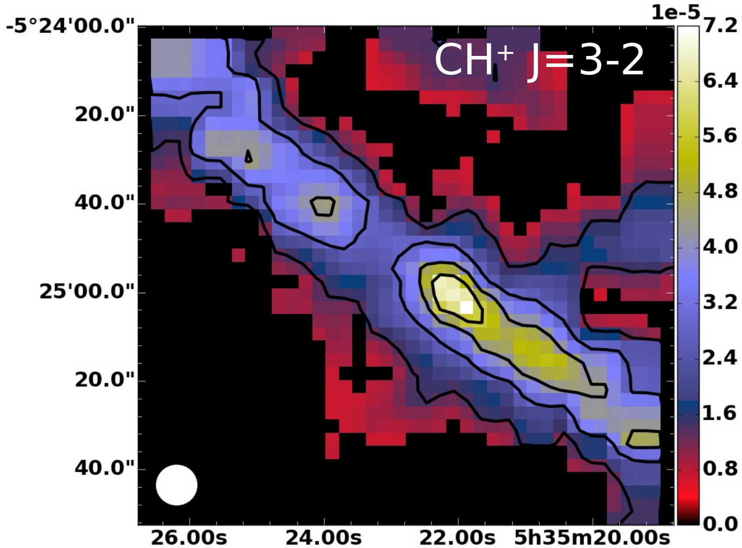
SPIRE observed lines (SSW & SLW):

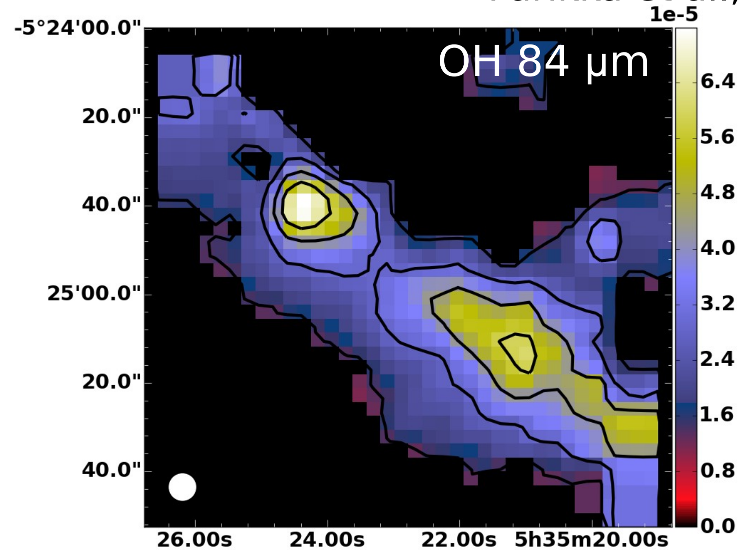
- ^{12}CO (J=4-3 to J=13-12)
- ^{13}CO (J=5-4 to J=13-12)
- $C^{18}O$ (J=5-4 to J=13-12)
- CH^+ J=1-0
- C^0 370 & 492 μm
- H_2O 269, 399, & 538 μm
- N^+ 205 μm

Spatial resolution 12” - 24”

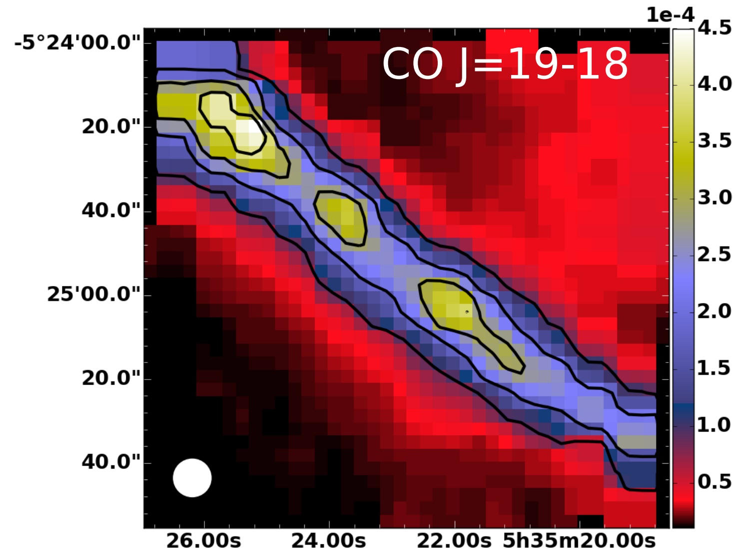
Mapping the Orion Bar with Herschel

Parikka et al., in prep.

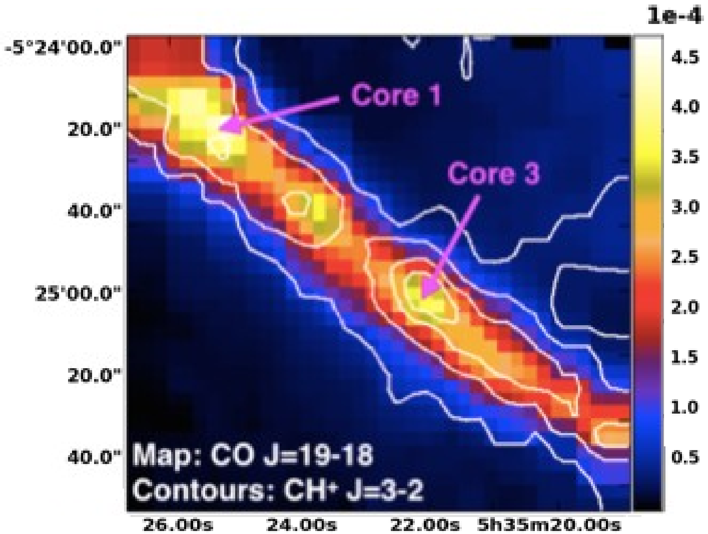


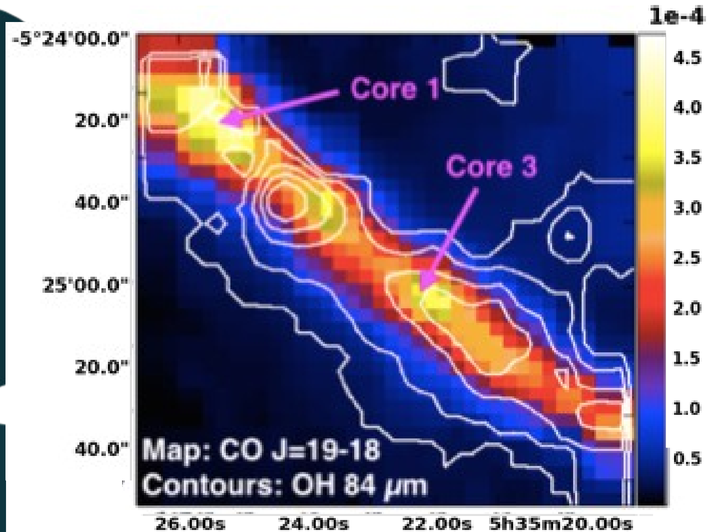


- First spatially resolved maps of these lines (PACS)
- Total area of 110” x 110”
- Spatial resolution of 6” to 9” (0.012 – 0.018 pc)
- Each map has a specific morphology dependent on the local conditions and processes



Origin of CH^+ and OH emission





Parikka et al. in prep.

- Similar properties:
  - n_{crit} ~10^{10} cm^{-3}
  - E_u ~250 K
- Both have a formation route with H_2
- Similar threshold:
  - CH^+ endothermicity: ~4300 K
  - OH activation barrier: ~4800 K

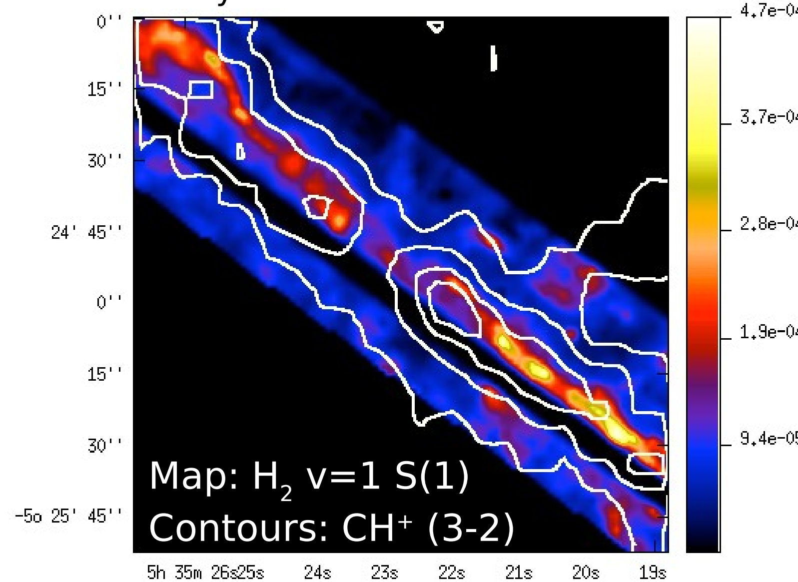
- Good correlation with high-J CO
- Emission peaks in clumps
- Originate in warm and dense gas

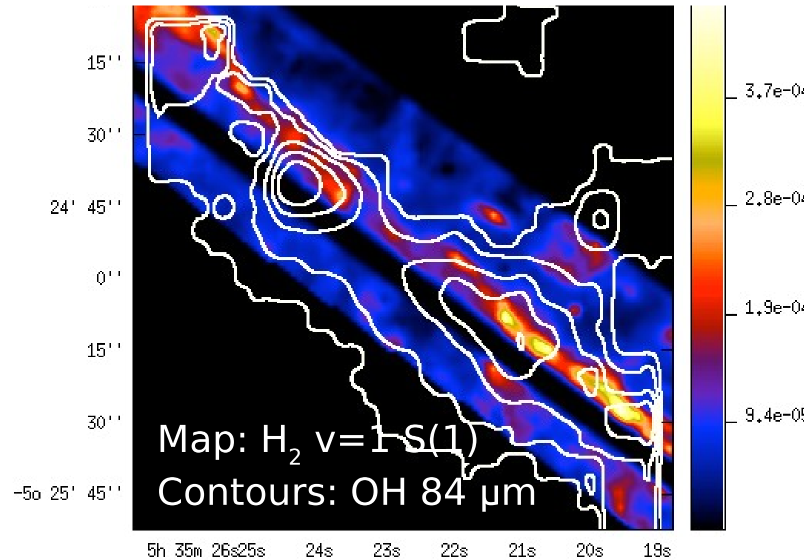
Comparison with vibrationally excited H_2

- 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^*

H_2 v=1 S(1) from Walmsley et al. 2000

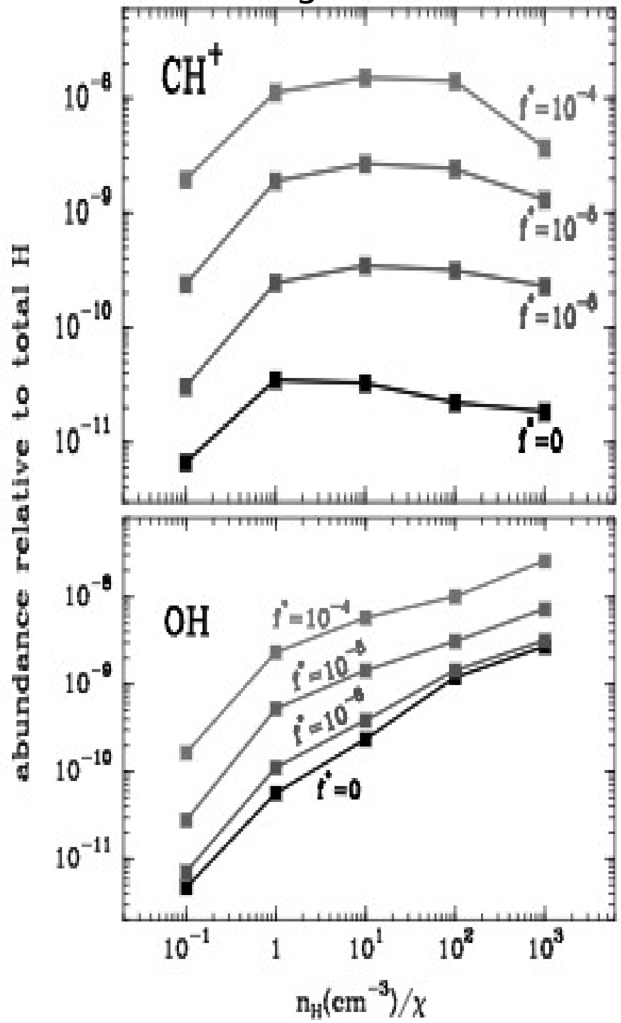
Parikka et al. in prep.





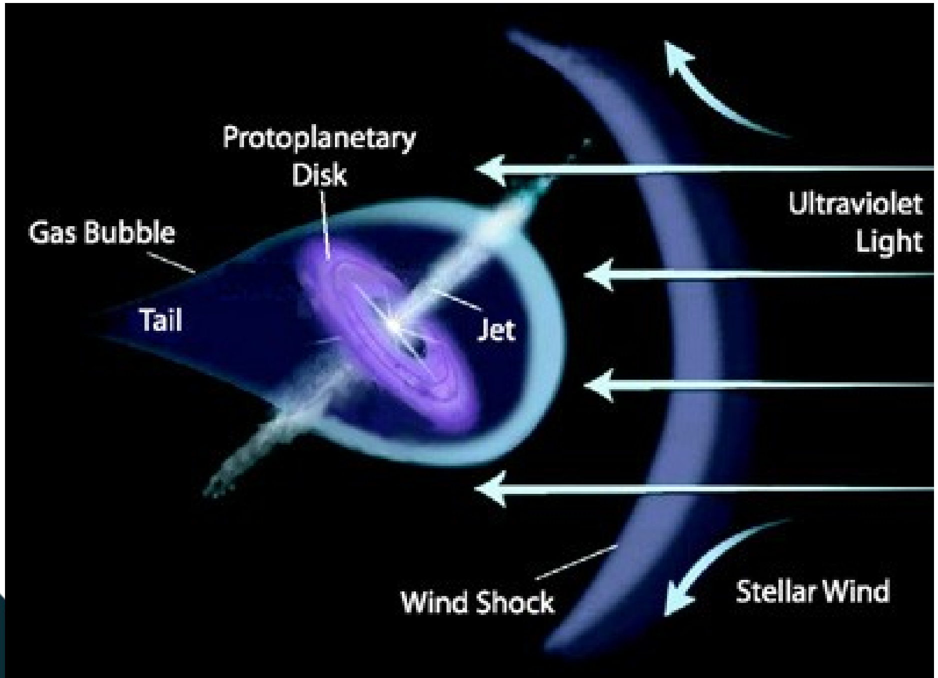
CH^+ and OH formation via vibrationally excited H_2

Agundez et al. 2010

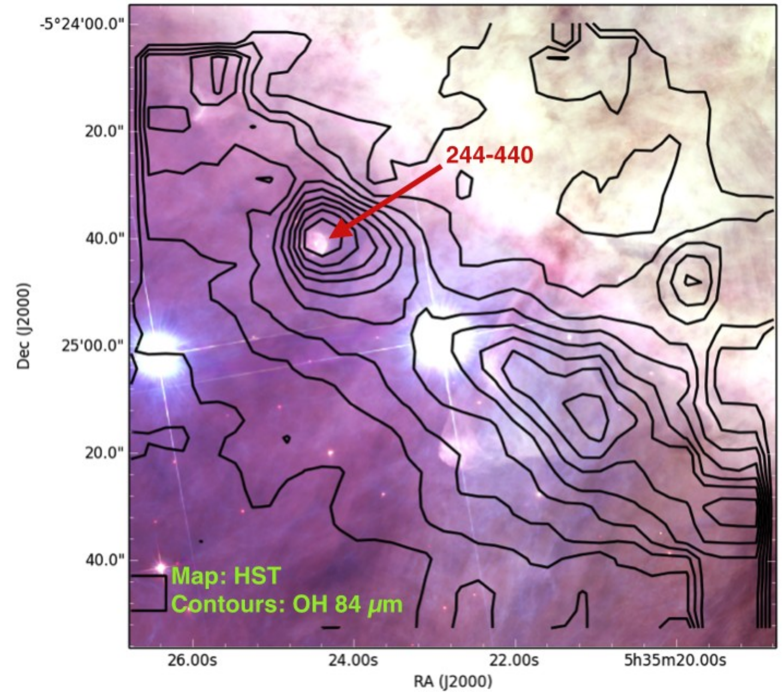


- CH^+ fractional abundance highly dependent on H_2
- OH much less dependent: energy activation barrier exists even when H_2 is v=3 (Sultanov & Balakrishnan 2005)
- Nagy et al. 2013:
  - CH^+ with H_2 formation (PDR code)
  - Wide line width could be due to chemical pumping (also our HIFI CH^+ J=2-1)

Unexpected proplyd detection



Parikka et al. in prep.



- 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

Spatial morphology of high-J CO

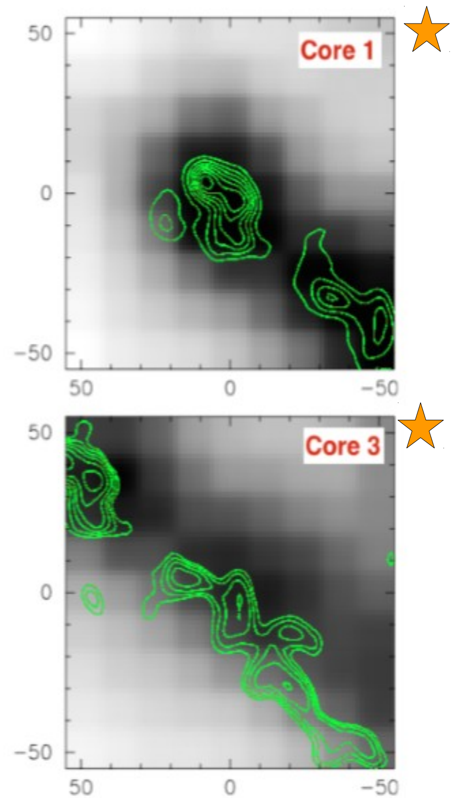
First time observed dense structures in high-J CO lines

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

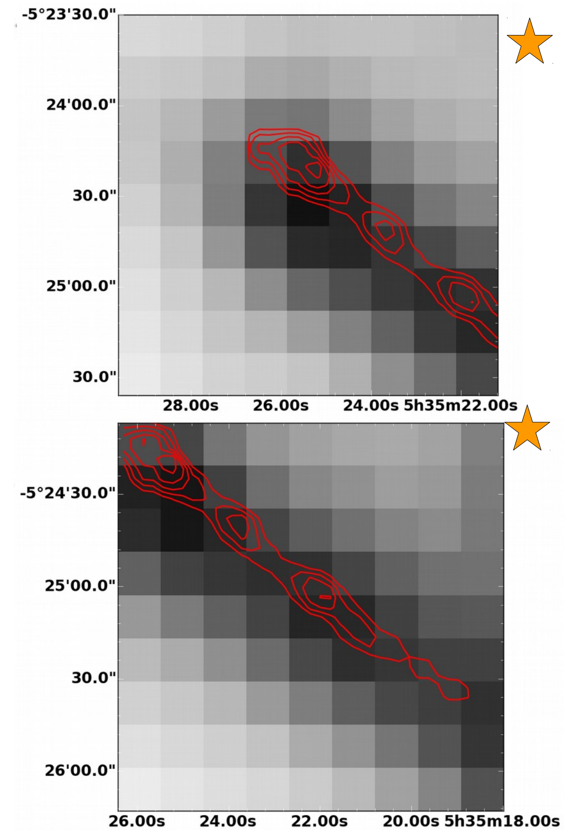
→ Link between the core and the edge of the dense clumps

CS (2-1) contours
on Herschel 500 μm



Lee et al. 2013

CO (19-18)
on Herschel 500 μm



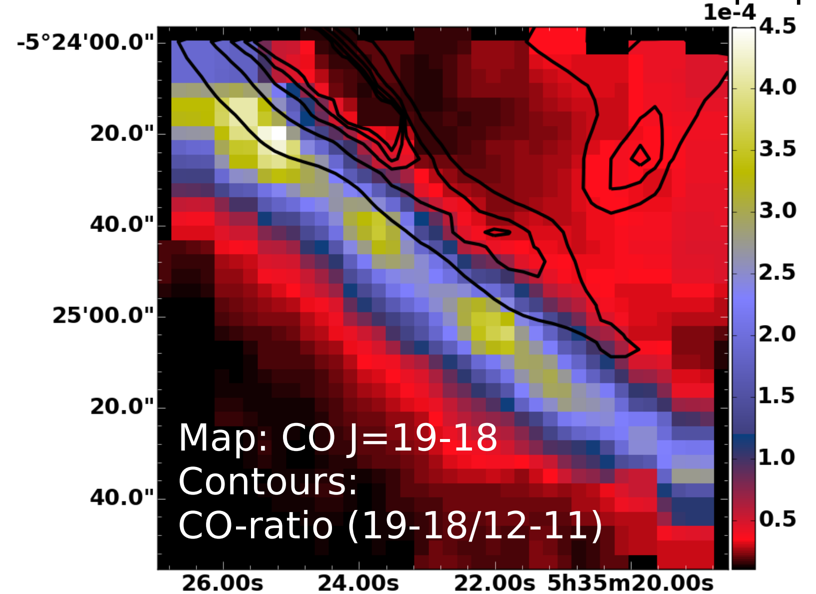
Parikka et al. in prep.

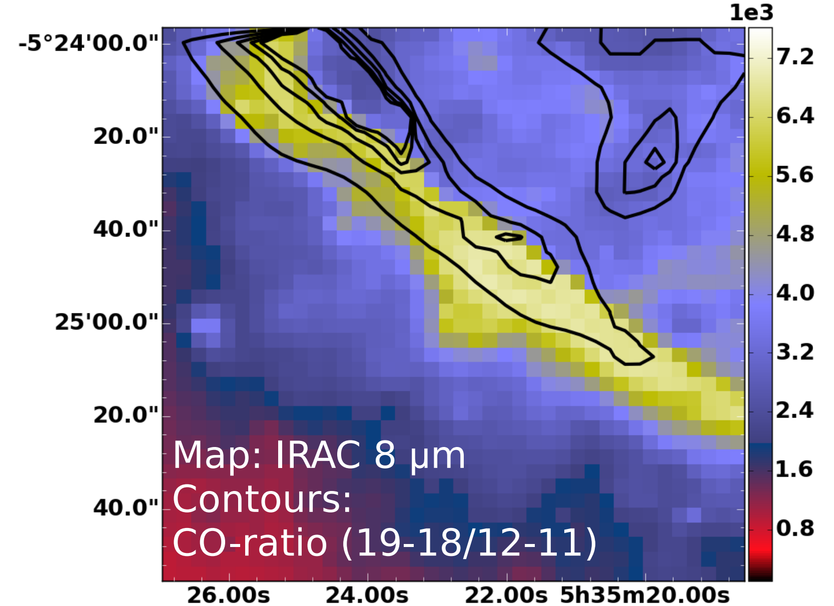
High-J CO excitation

Parikka et al. in prep.

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) 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)

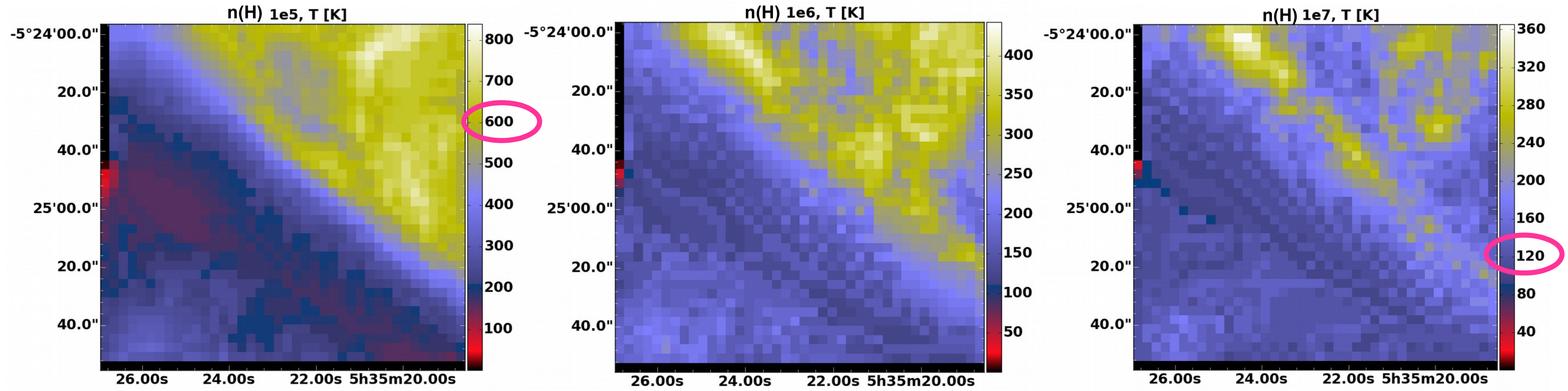




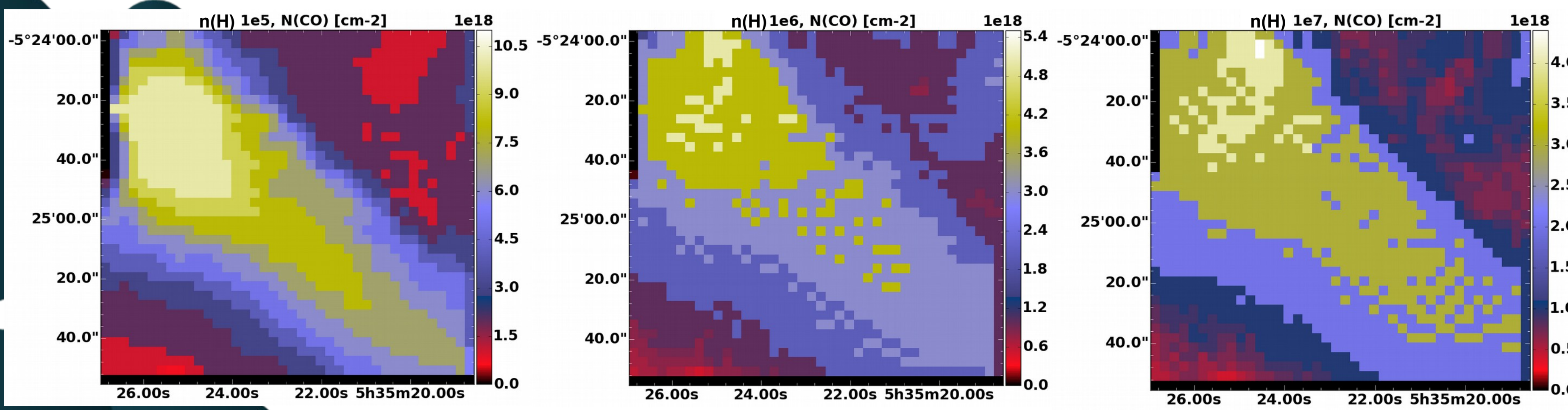
RADEX results

Temperature maps

Parikka et al. in prep.



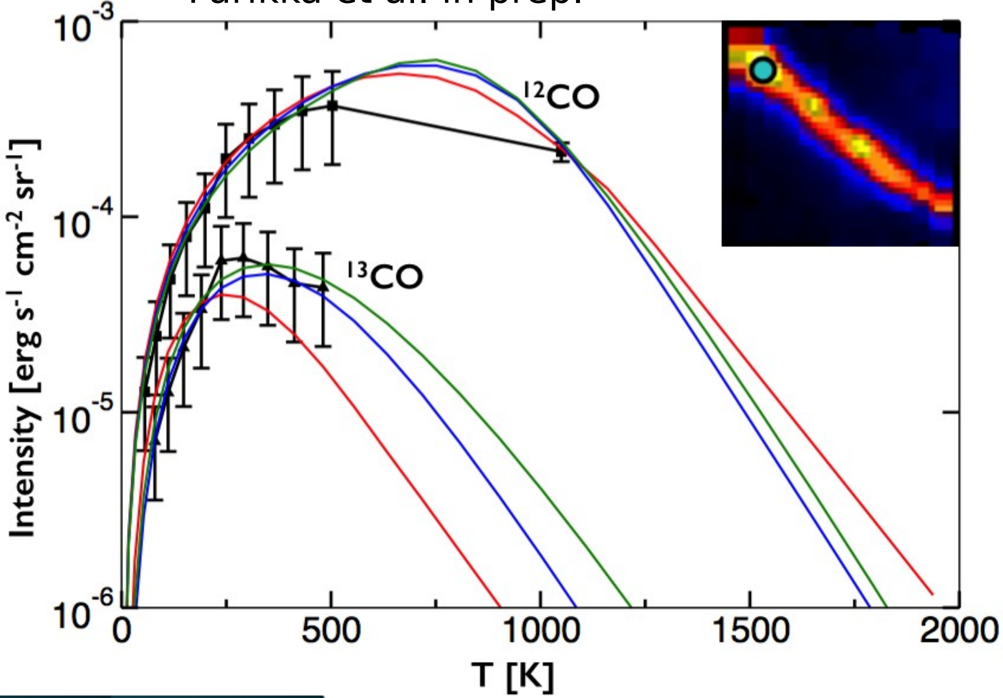
Column density maps



RADEX results

n_H [cm^{-3}]	N_{CO} [10^{18} cm^{-2}]	T_g [K]	η	P [$K\ cm^{-3}$]	l [pc]	l [″]
10^5 **red**	10	230	0.3	2.3×10^7	0.58	230
10^6 **blue**	4	160	0.4	1.6×10^8	0.026	13
10^7 **green**	4	120	0.5	1.2×10^9	0.003	1.3

Parikka et al. in prep.



- 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 ~2×10^8 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)

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)

Channels	Frequency Range [THz]	T_{rec} [K], DSB*	Astronomical Lines of Interest
Low-frequency L1	1.25 – 1.39	600	CO(12-11), OD, SH, H_2D^+, HCN, HCO^+
	1.42 – 1.52	600	CO(13-12), [NII]
Low-frequency L2	1.80 – 1.90	700	NH_3(3-2), OH($^2\Pi_{1/2}$), CO(16-15), [CII]
Mid-frequency Ma	2.49 – 2.56	1500	$^{(18)}$OH($^2\Pi_{3/2}$)
Mid-frequency Mb	2.67 – 2.68	3100	HD(1-0)
High-frequency H	4.745	1000	[OI]

Backends: Fast Fourier Transform Spectrometers	Bandwidth [GHz]	Resolution [MHz]
AFFTS	1.5	0.212
XFFTS	2.5	0.044
FFTS4G	4.0	0.244

upGREAT

- 1.9 THz multi-pixel high resolution spectrometer

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

Species	Rest Freq.	Transition	Comment
OH	1.834 THz		
CO	1.841 THz	$J = 16 - 15$	
CII	1.9005 THz	$J = 3/2 - 1/2$	
CO	1.955 THz	$J = 17 - 16$	
HeH^+	2.01 THz		undetected in the ISM
OI	2.06 THz		
CO	2. 07THz	$J = 18 - 17$	barely doable
CO	2.19 THz	$J = 19 - 18$	blocked by atmosphere
CO	2.42 THz	$J = 20 - 21$	not tunable yet
NII	2.459 THz	$J = 2 - 1$	blocked by atmosphere
OH	2.49 THz		not tunable yet
OH	2.51 THz		not tunable yet
CO	2.52 THz	$J = 21 - 20$	not tunable yet

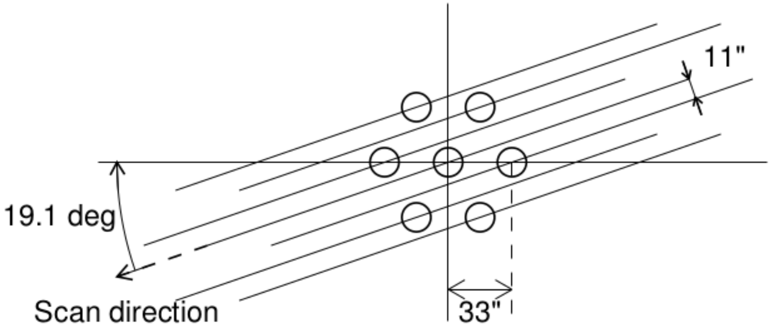
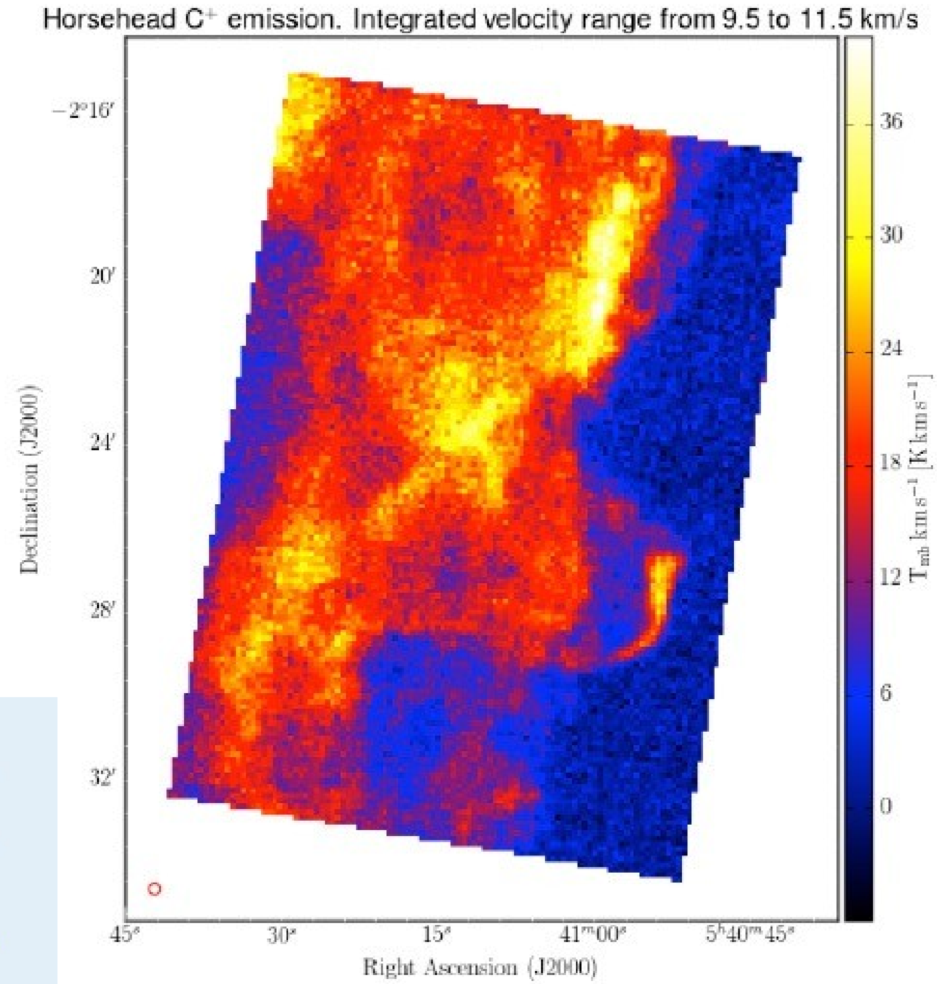


Fig. 7. Sketch of the array-OTF mapping mode. Circles indicate the beam sizes in the hexagonal array pattern. The beam spacing is 33″.

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



Max-Planck-Institut für Radioastronomie

Kölner Observatorium für Submm-Astronomie Universität zu Köln

Max-Planck-Institut für Sonnensystemforschung

DLR-Institut für Planetenforschung