C and H Reactives in Orion KL

C^+ and Methylidyne CH^+ Mapping with HIFI

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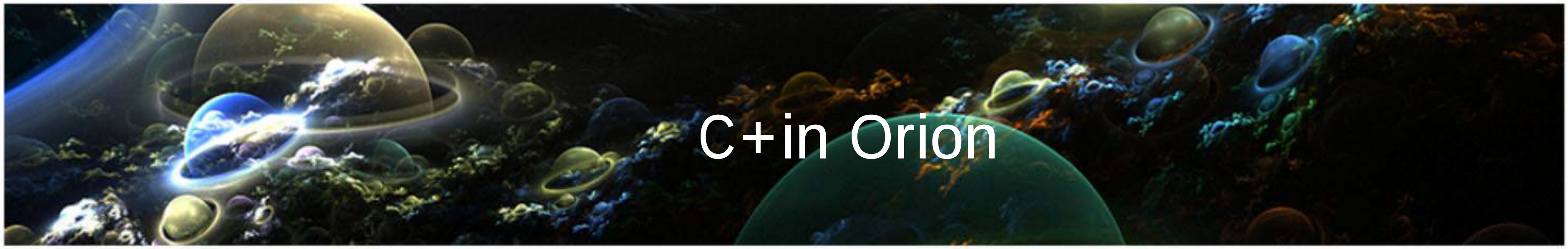
and HIFI Calibration team

Outline

Orion KL nebula contains one of our nearest (~450 pc) / dearest massive SFRs

BN object, numerous embedded (0.2 pc) IR/radio, hot cores and X-ray sources, luminous IRc2 source with ~900 yr outflow 10^{-3} $M_\odot$/yr driven by ~20 $M_\odot$ protostar, K/M dwarfs, SiO & methanol masers, at least ~100 probable protostars within ~0.5 pc of the ionizing O7Vp star θ^1 Ori C (binary), ~20 massive OB stars --- something for everyone!

- C+ mapping of Orion KL
  - Intensities, velocities at HIFI's excellent spectral and spatial sensitivities.
  - $^{13}C^+$ detections, and the $^{13}C/^{12}C$ abundance ratio.
- Early results with CH^+ mapping observations.
  - Detections, distribution, velocities vs. C^+
  - "Serendipitous" observations of methanol, tracing hot gas/grain interactions and/or shocks --- contrast with C^+, shocked H_2 emission



C+in Orion

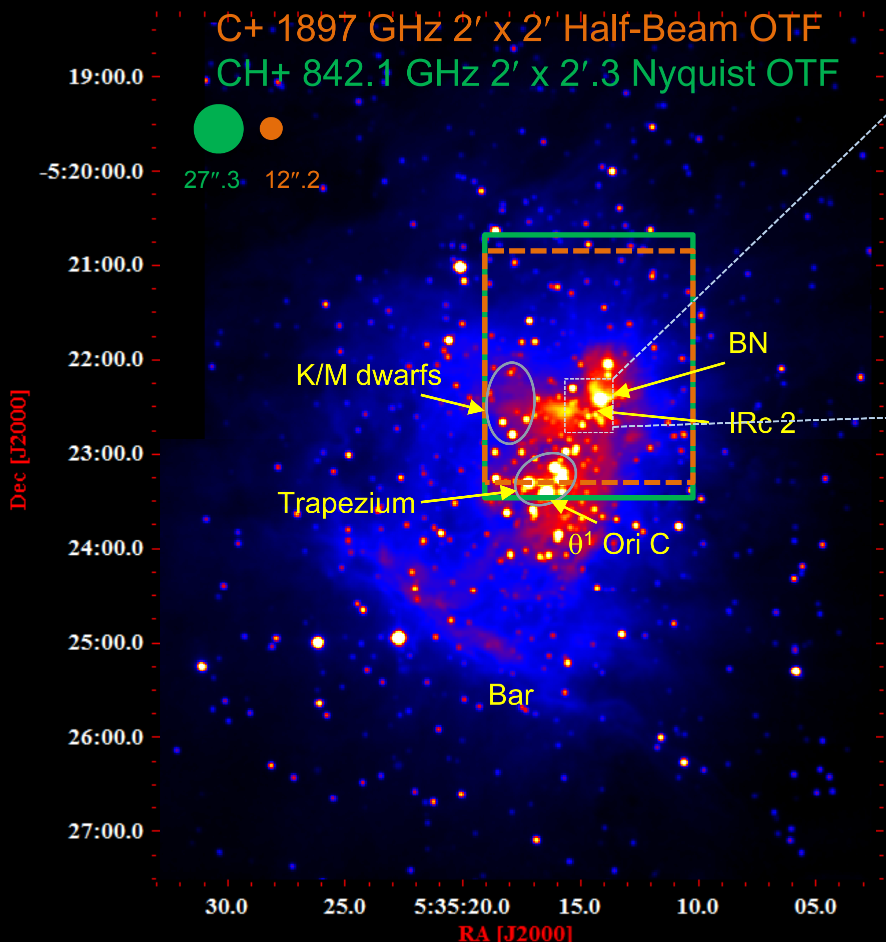
- [CII] $^2P_{3/2} - ^2P_{1/2}$ cooling line traces distribution of warm (T_g ~350 K) dense (n_H ~ $2x10^5$ cm^{-3}) photo-dissociated regions created by UV radiation on the surfaces of GMCs. Intensity scales with PDR density, emission can also originate in shocks from jets/outflow regions.
  – HIFI sensitivity, 12” beam (@ 1900 GHz) provide excellent mapping capabilities, and ~1 km/s spectral resolution (Wide Band Spectrometer):
    ☞ trace cloud velocity structure and strength of the C+ lines.
    ☞ $^{12}C/^{13}C$ ratio to test PDR models for competing effects of chemical fractionation and isotope-selective photodissociation. E.g. Keen et al. (1998) Orion Bar.
  – Several earlier C+ observations in Orion, notably
    - Stacey et al. (1993) KAO Fabry-Perot inner 6’.5 x 10’, 44” beam
    - Boreiko & Betz (1996) KAO heterodyne 44” beam, $^{12}C^+/^{13}C^+$ ratio near θ^1 Ori C
    - Lerate et al. (2006) ISO/LWS Fabry-Perot, 80” beam centered on/near IRc2

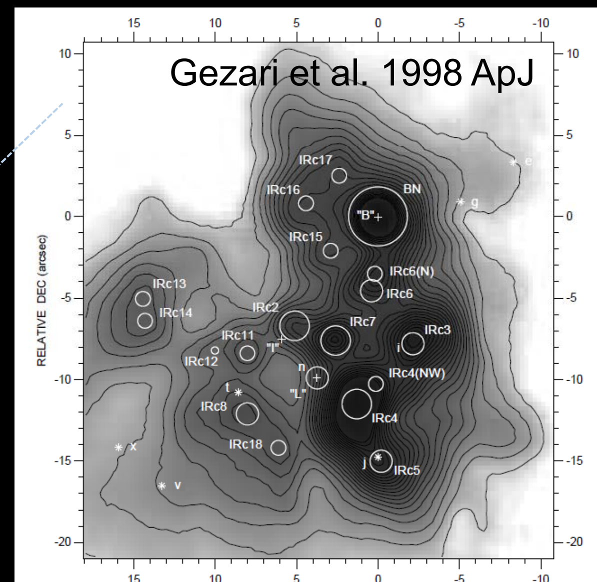
Mapping the storm

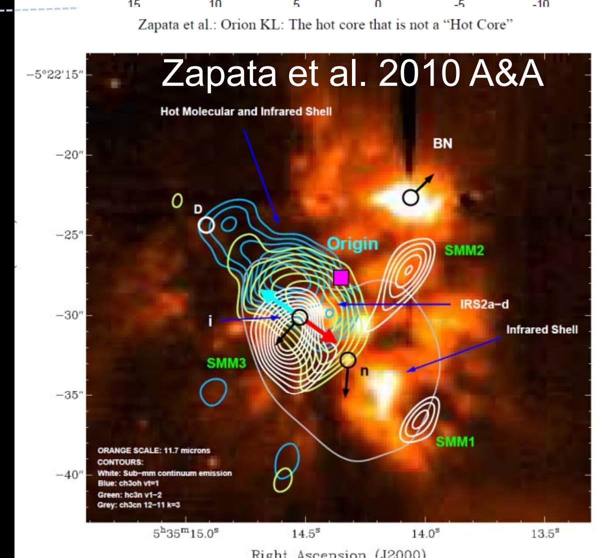
HIFI OTF mode (position switch)

CH+: 842 GHz (band 3a) @ Tsys 250 K, 2.5 hr, SSB noise 100 mK

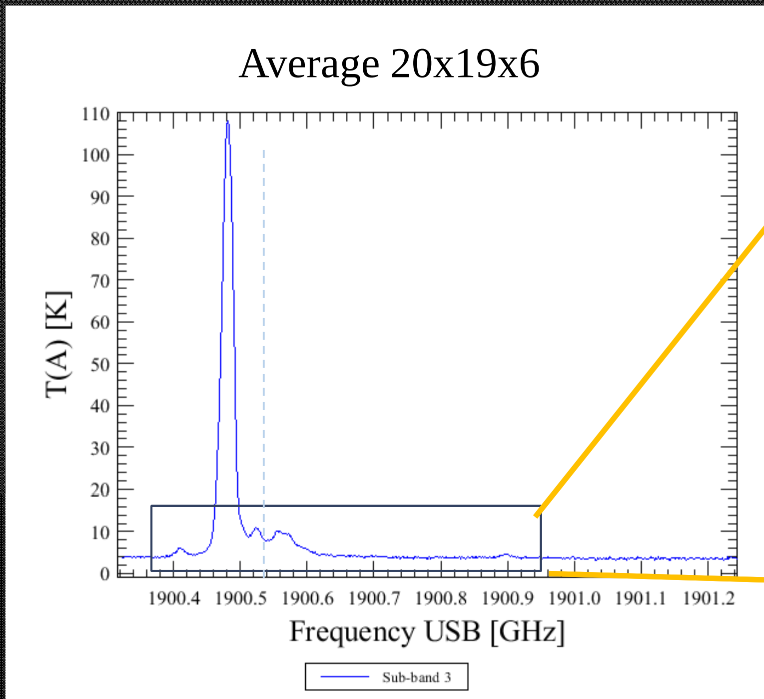
C+: 1897 GHz (band 7b) @ Tsys 1600 K, 26 min, SSB noise 500 mK

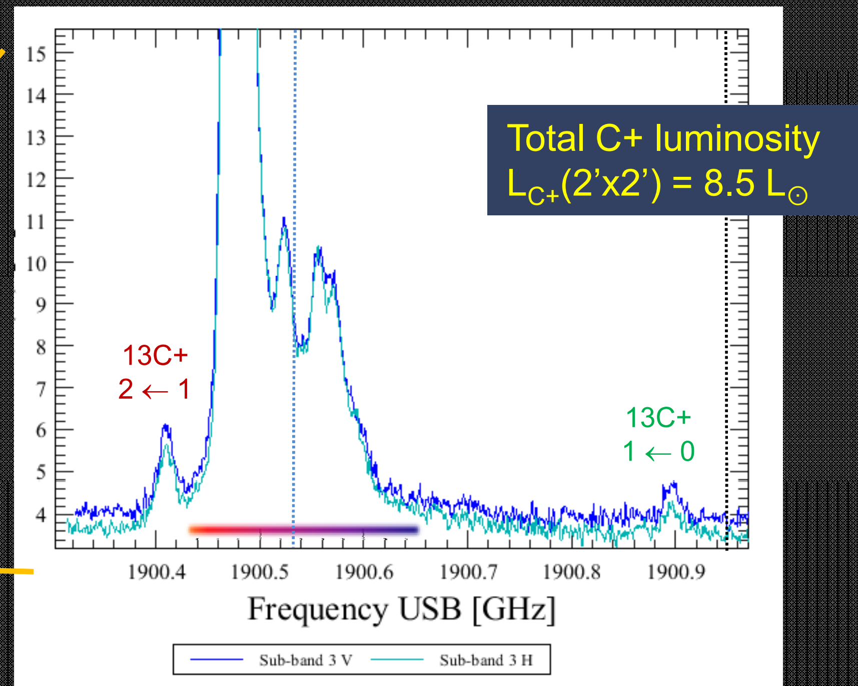






$^{12}C^{+}$, $^{13}C^{+}$ observed

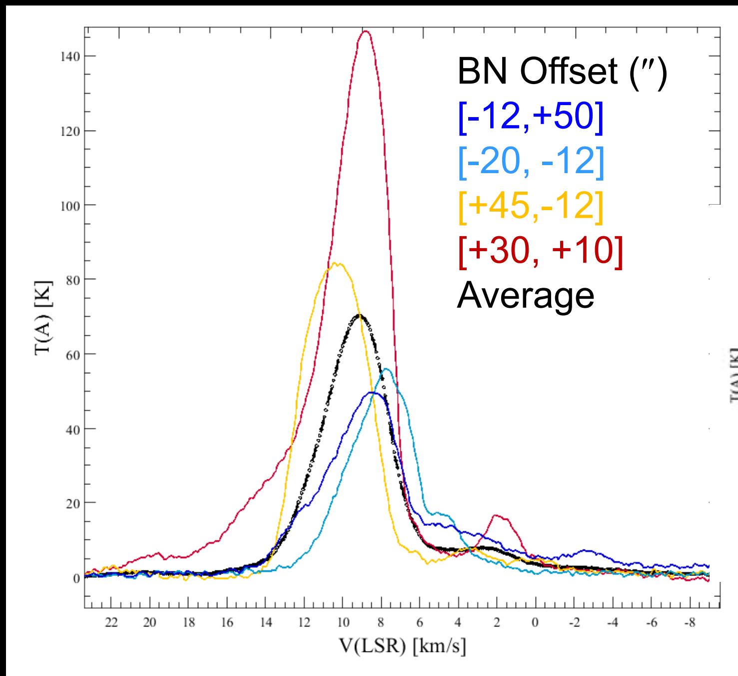


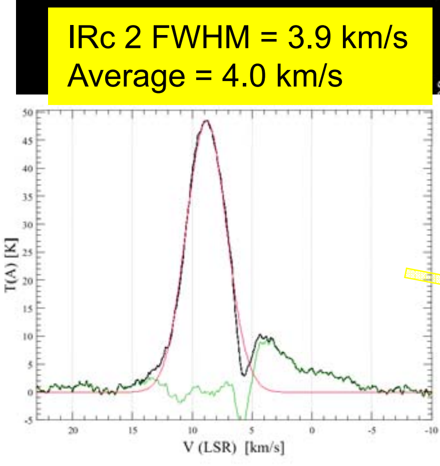


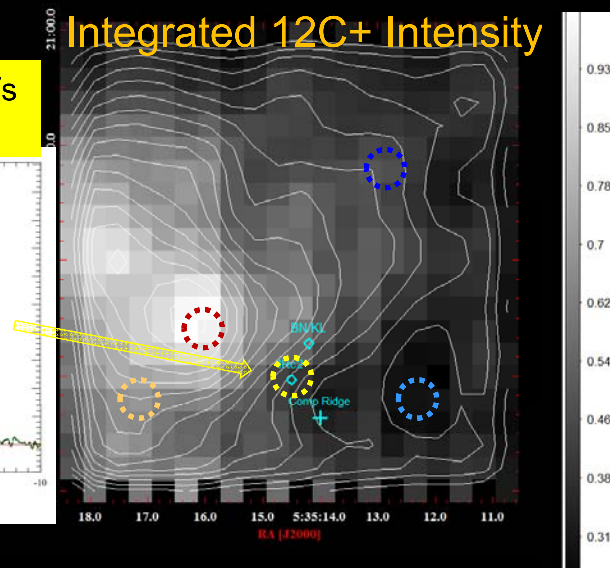
Main component agrees with velocity of the quiescent gas

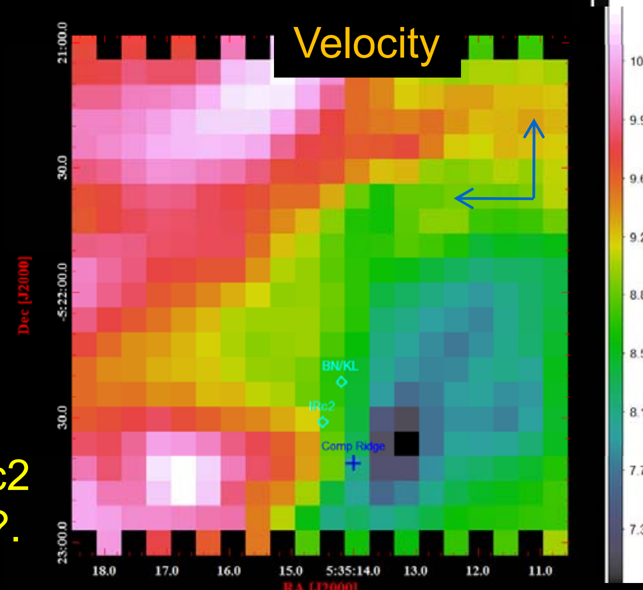
	V_{LSR} [km/s]	Peak intensity [K] (1-σ uncert)	Integrated Intensity (% total)		
			[K km/s]	[10^{-19} W/cm2]	% total
12C+	– [1-3]	10 (1)	42	1.4	11.5
	+[0.5-4.5]	20 (2)			
	+[9.0-11.0]	180 (12)	313	10.3	85
	+[11.0-15]	~40 (5)			
13C+ 2←1	+9.5	5 (1)	5.5	0.2	1.5
13C+ 1←0	+9.5	~1 (0.2)	2.0	0.07	0.5

Some basic features of the HIFI C+ map







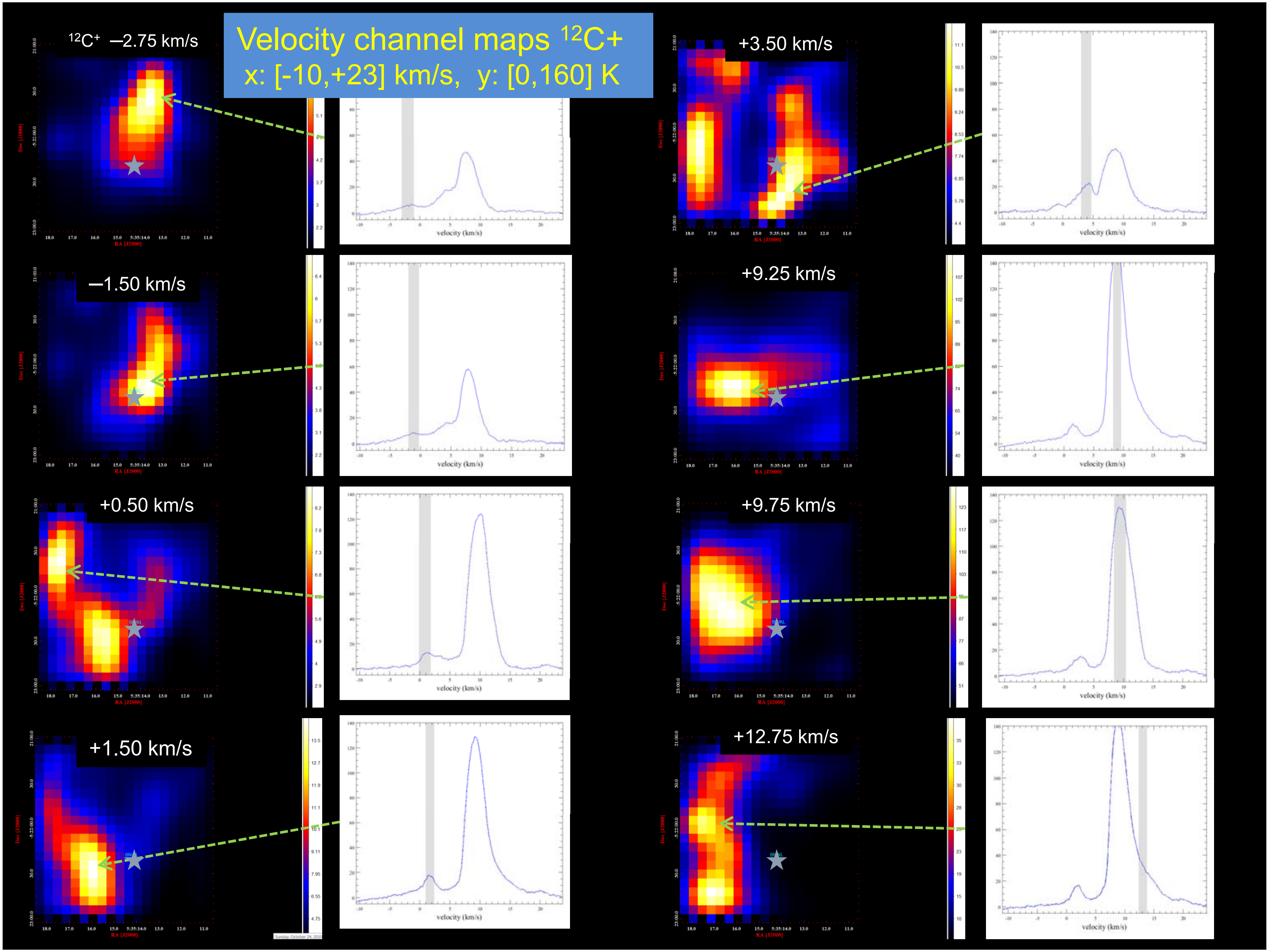


C+ emission is widespread over entire region

- Clumpy, large intensity variations. Velocity field is dominated by main component 7-13 km/s.
- High intensities support PDR model

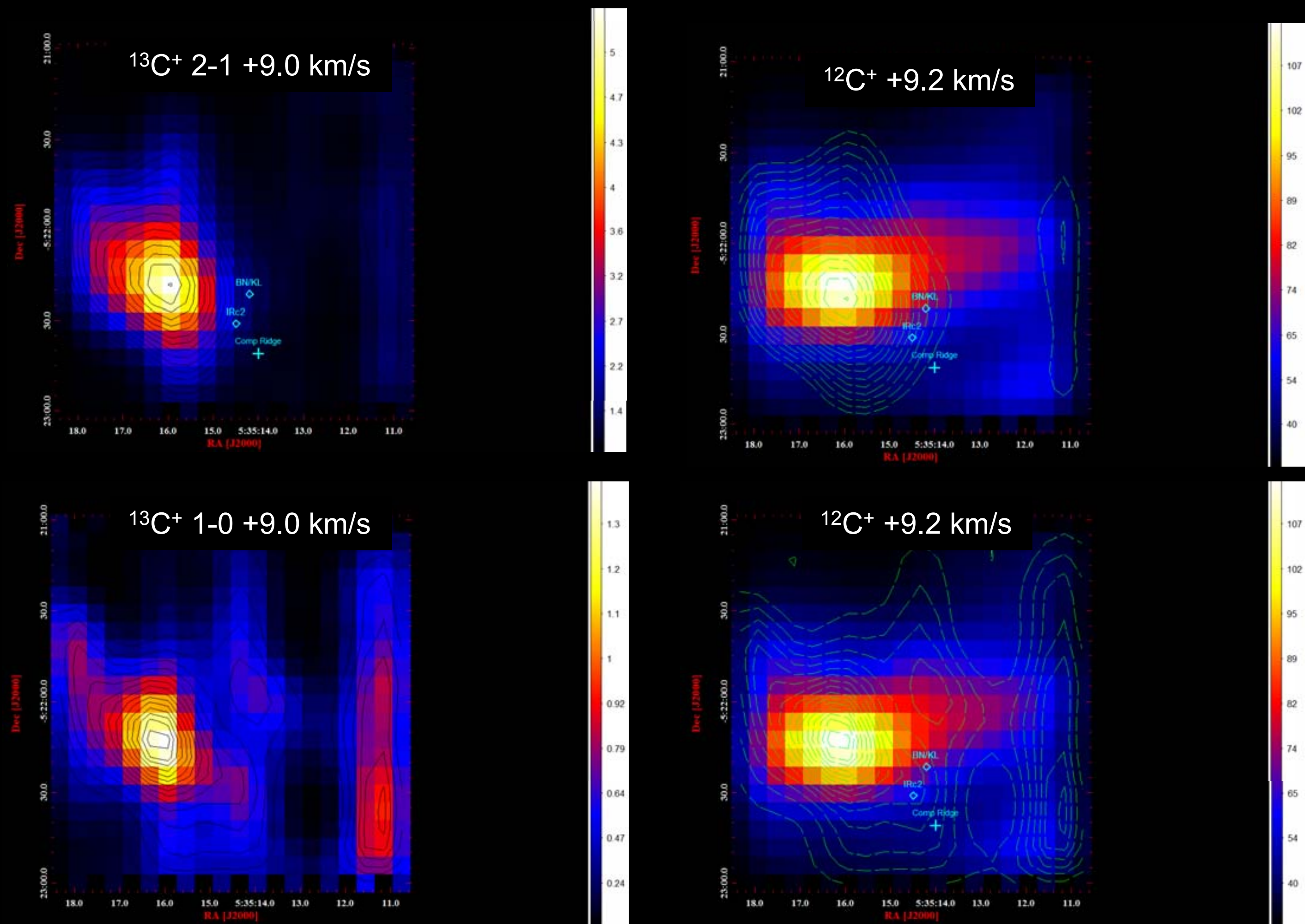
Higher densities ($n_0 \gtrsim 10^6$ cm^{-3}) than estimated for the region and higher velocities required for J shocks to boost emission (e.g. Hollenbach & McKee 1989).

Low (but not lowest) intensities, slowest material around IRc2 outflow source --- diffuse foreground or shock component?. The line profiles reveal nothing obvious about this.

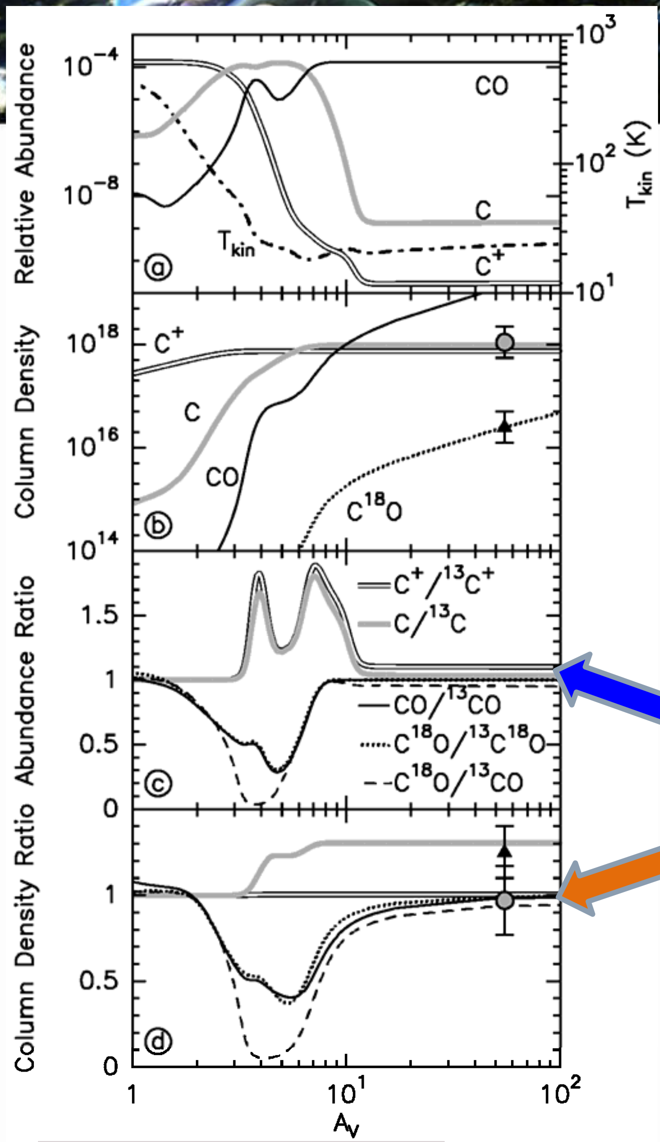


Velocity channel maps $^{12}C+$
x: [-10,+23] km/s, y: [0,160] K
$^{12}C^{+}$ –2.75 km/s
–1.50 km/s
+0.50 km/s
+1.50 km/s
+3.50 km/s
+9.25 km/s
+9.75 km/s
+12.75 km/s
velocity (km/s)

Velocity channel maps $^{13}C+$



The 12/13 C ratio



Keene et al. 1998 ApJ

- Keene et al. (1998 ApJ) PDR model (using code of Le Berlout et al. 1993, A&A) for Orion Bar region:
  - $n(H_2)$ =2.5x10^4 cm^{-3}, T_g = 120 K
  - UV field of strength G_o = 4x10^4
  - abundances from Flower et al. (1995, A&A)
  - Total gas-phase isotopic abundance ratios $^{12}C/^{13}C$ = 60 and $^{16}O/^{18}O$ = 500.
  - Incorporates chemical fractionation and isotopic-selective photodissociation, mutual- and self-shielding of H_2 and all the CO isotopomers.
- The abundance ratios of $^{12}C^+/^{13}C^+$ closely follows that of $^{12}C/^{13}C$, however the column density ratio of $^{12}C^+/^{13}C^+$ is *unaffected* by the PDR.
- This is because C^+ is most abundant *outside* the molecular cloud where it is a majority species and PDR effects on the ratio are negligible.
- ☞ The isotopic column density ratio measured in C+ should give the true isotopic gas-phase abundance ratio.

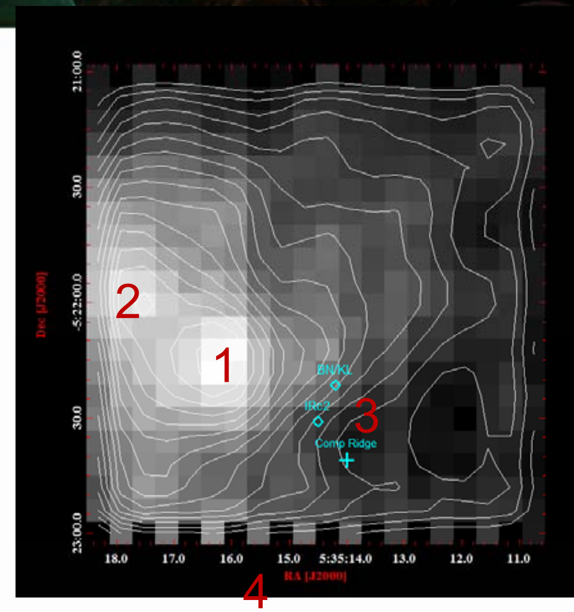
12C+/13C+ ratios

- ^{12}C/^{13}C abundance ratio R can be calculated from the observed ^{13}C$^+$/^{12}C$^+$ intensity ratio I_{13}/I_{12}:

$$R = \frac{-\tau_{12}}{\ln\left[1 - \frac{I_{13}}{I_{12}}\left(1 - e^{-\tau_{12}}\right)\right]}$$

* Peak optical depth τ_{12} = 1.3 for the ^{12}C$^+$ line, based on best fit PDR model with T = 185 K to match O^0 and C$^+$ lines at θ^1 Ori C (Boreiko & Betz 1996 ApJ).

* I_{12} = composite ^{12}C$^+$ velocity components [-2,+12] km/s. I_{13} = composite F=2←1, 1←0, 1←1 ^{13}C$^+$ lines.



	Location	R (1σ)
	Average	**55 (±4)**
1	12C+ peak	57 (±4)
2	13C+ peak	50 (±5)
3	IRc2	No 13C+
4	θ^1 Ori C (BB98)	58 (+5/-6)

* Overall agreement with Boreiko & Betz (1998) for θ^1OriC

* Keene et al. (1996) : same for neutral ^{13}C/^{12}C at Orion Bar.

☞ Agreement of isotope ratios from neutral and ionized C indicate fractionation of ^{13}C$^+$ into ^{13}CO at cloud edges is not important, or offset by selective photodissociation of ^{13}CO.

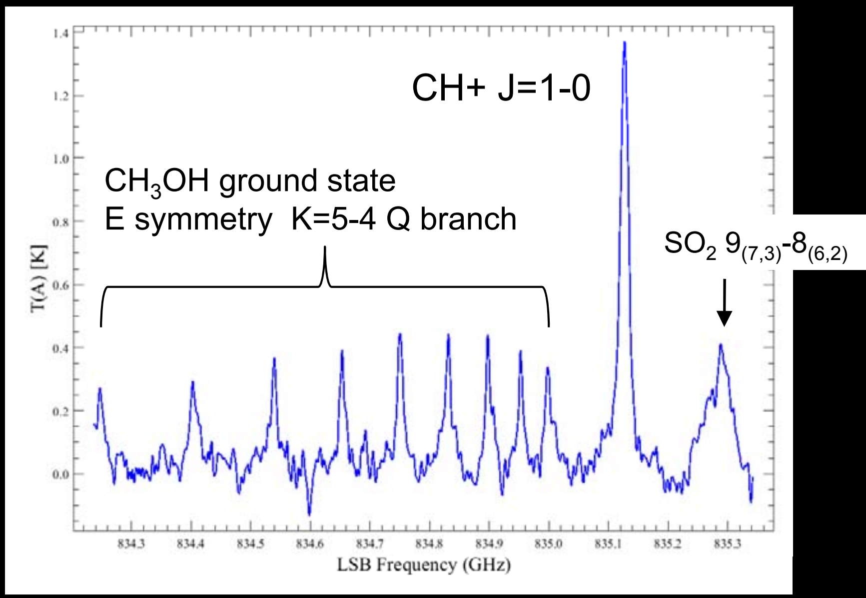
* Variations at 2σ measurable over the HIFI map, R = 50-60. Optical depth effects, or attenuations by fractionation, photodissociation?

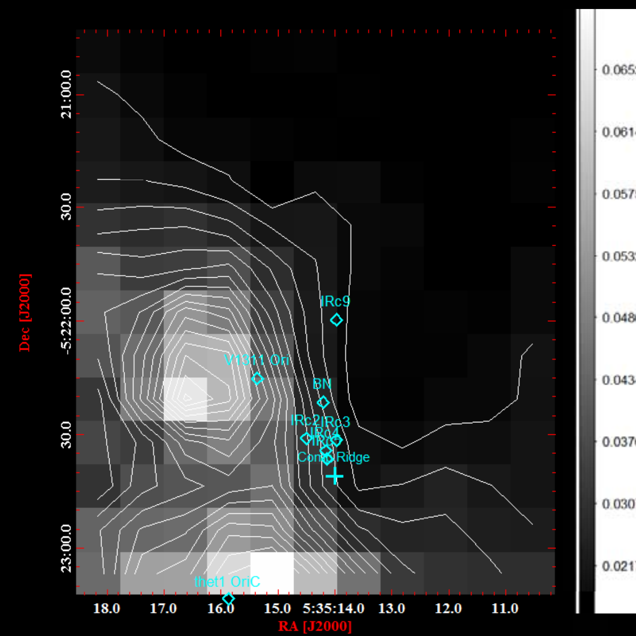
Methylidyne cation CH^+ detections in Orion KL

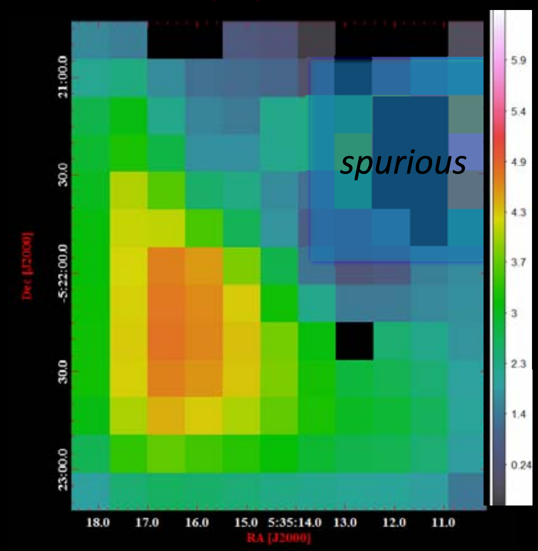
- Chemistry of highly reactive CH+ is not well understood
- Usually correlates with rotational H_2 ☞ formation in energetic regions.
  - If formed in shocks, should expect velocities different from CH (shock source). So far not the case, and the lowest levels in both CH and CH+ in emission, higher levels are in absorption, which doesn't work very well if CH is reacting with molecular hydrogen.
  - The mean UV field of the ISM is too weak for UV pumping to produce excited H_2. Lab measurements of $C^+ + H_2(\nu=1) \rightarrow CH^+ + H$ may support CH+ formation in PDRs.
  - Turbulence dissipation models may support CH+ formation in the ISM --- talk by E. Falgarone.

- **CH^+ J = 1-0 835.137 GHz line mapped with HIFI towards BN/KL.** "Serendipitous" CH_3OH and SO_2 also present (same sideband).
  - CH $\Pi^{1/2}$ J = 3/2 - $\Pi^{3/2}$ J=3/2 1470/77 GHz fixed observations Orion KL (HEXOS).
  - CH^+ J = 1-0 and 2-1 (1669.2 GHz) also in W31C, DR21OH, Sgr B2 , S140, Orion Bar (PRISMAS, WADI). CH+ J=2-1 absorption observed by Falgarone et al (2005 ApJ).
  - SPIRE FTS observations CH 1470/77 GHz, CH+ 835 GHz in Orion Bar (Naylor et al. 2010 A&A).

CH+ observed properties



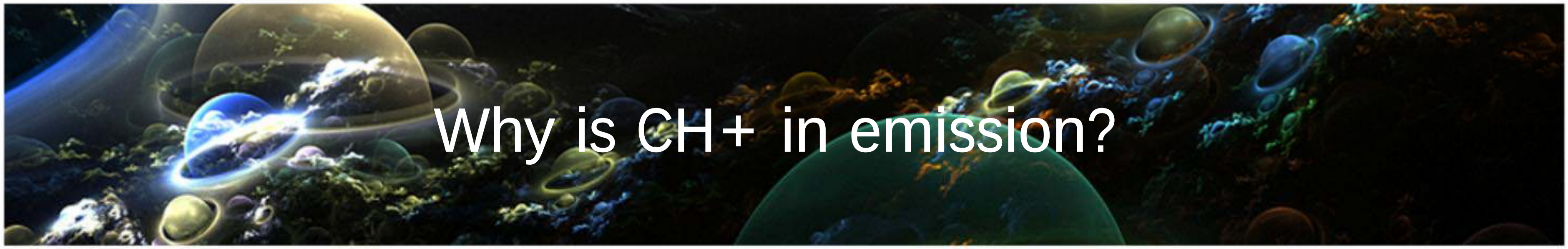




- CH+ is widely distributed, peaks at the same location as C+, ~35″ NE of BN/IRc2. Also peaks towards θ^1 Ori C.
- One main component: V_{LSR} average = +4.1 km/s, FWHM = 6.2 (±1.5) km/s.

☞ CH+ intensities and velocities distributed more smoothly than C+.

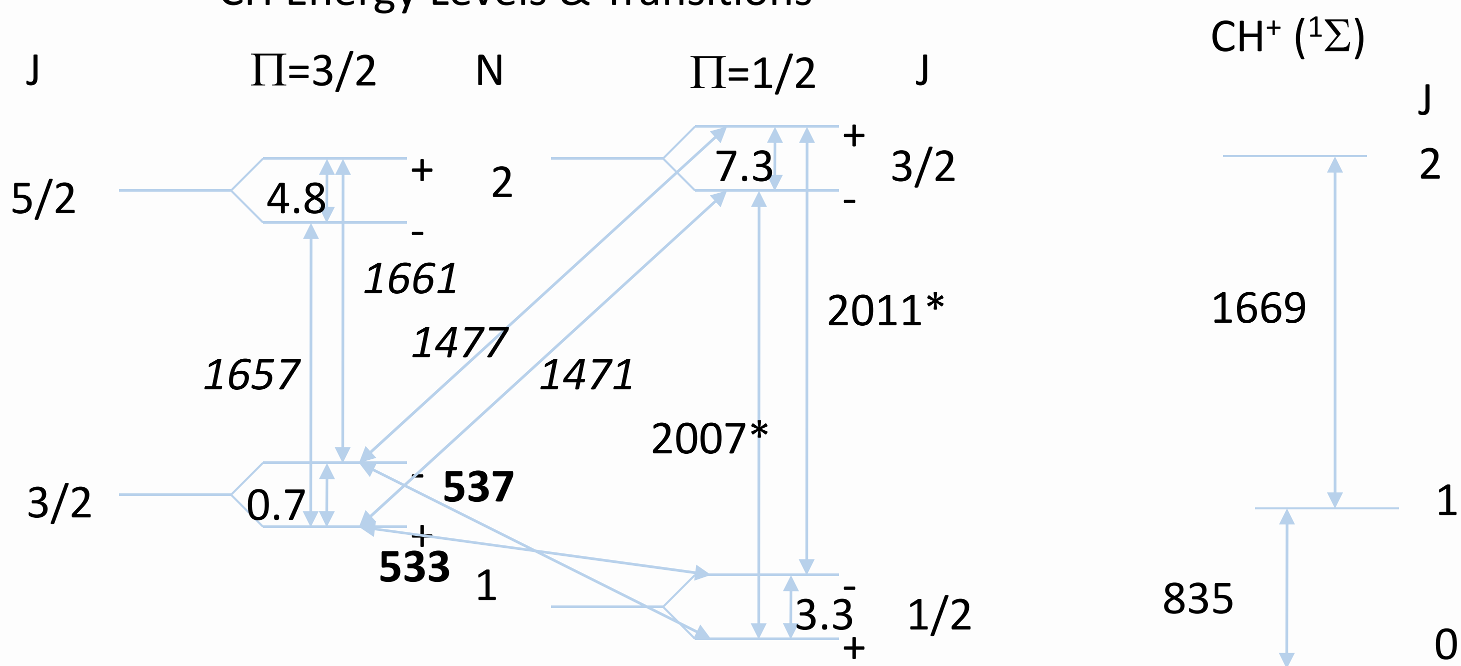
☞ There is a very strong contrasting gradient in the distribution of methanol…



Why is CH+ in emission?

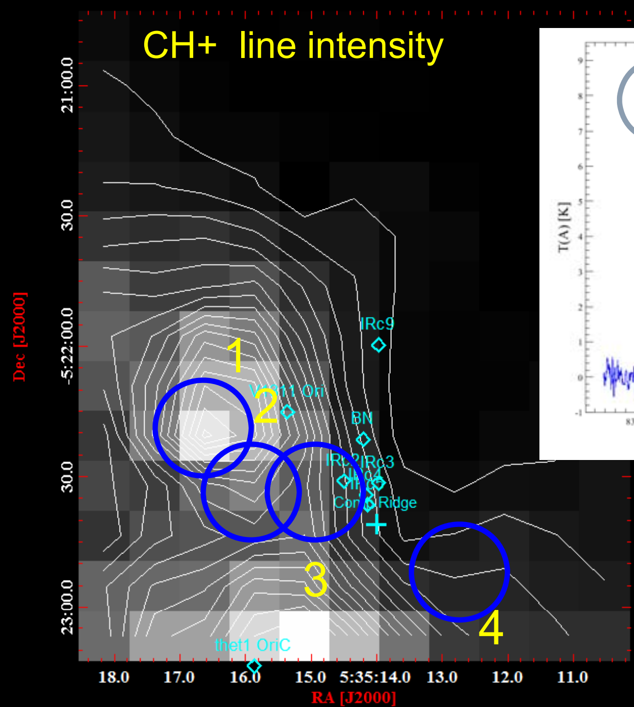
$C^+ + H_2 \rightarrow CH^+ + H$ is highly endothermic, 0.4 eV barrier

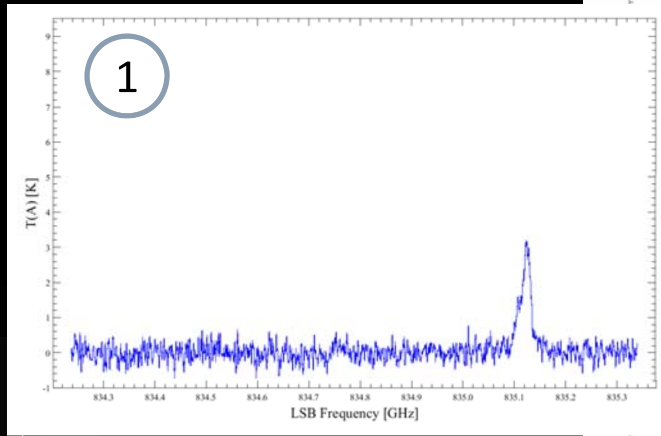
CH Energy Levels & Transitions

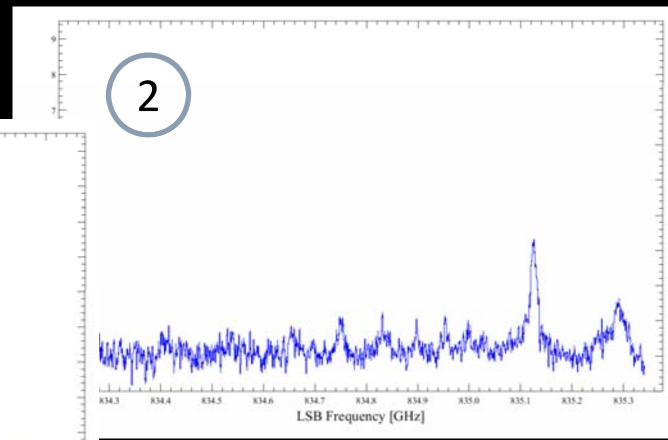


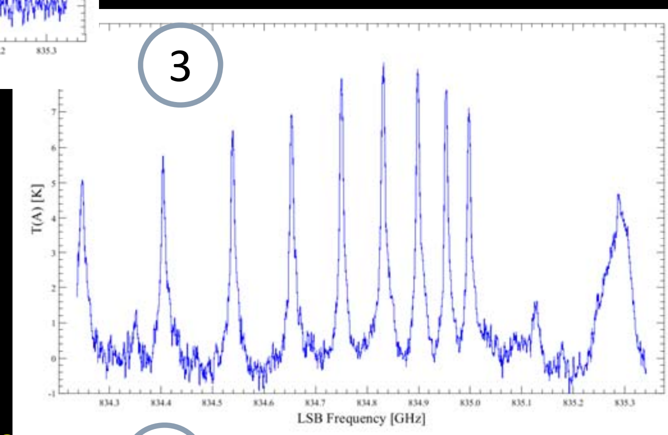
Bold=Emission
Italics=Absorption
* Not covered by HIFI

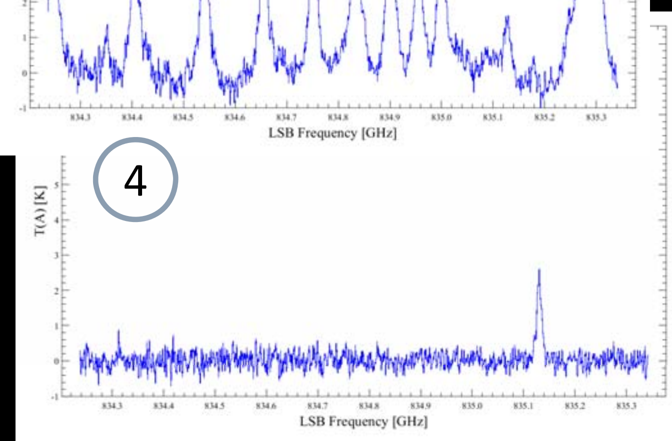
CH^+ vs methanol









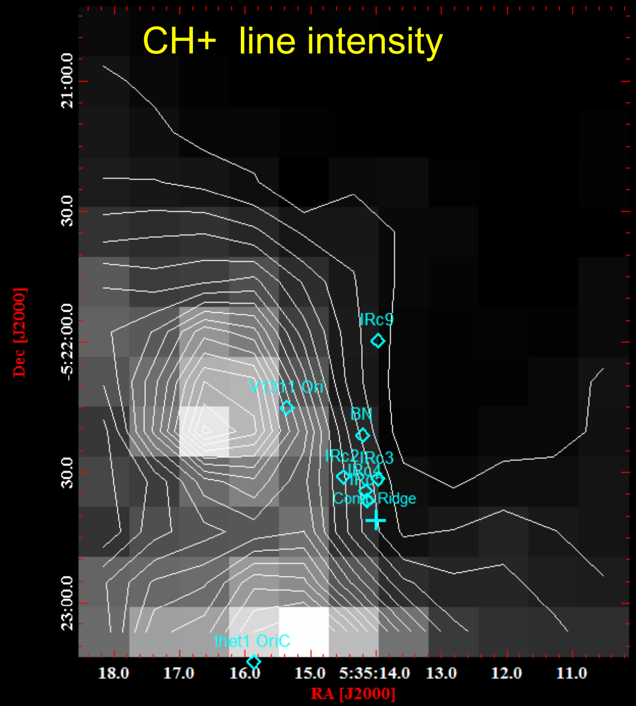


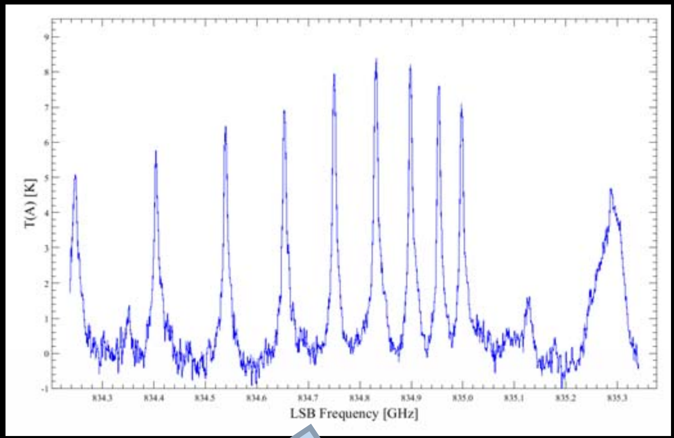
- Distribution of methanol is localized to the IRc2 / Compact Ridge region. Traces surface grain reactions.

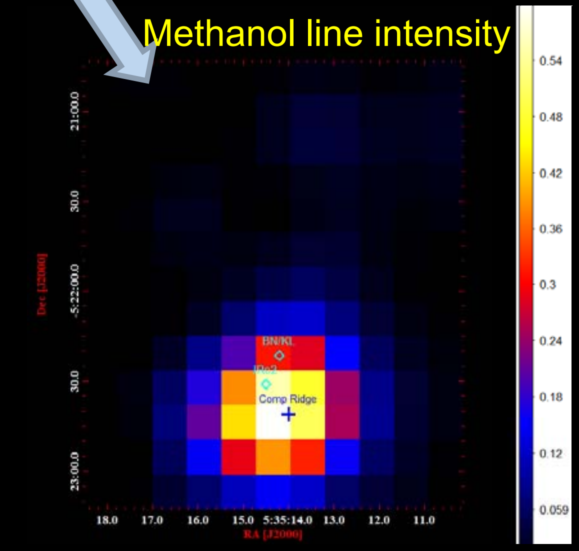
☞ High density hot core region, $n(H_2)$ ~few $10^5 – 10^6$

☞ Able to support some C^+ formation in J shocks?

CH^+ vs methanol







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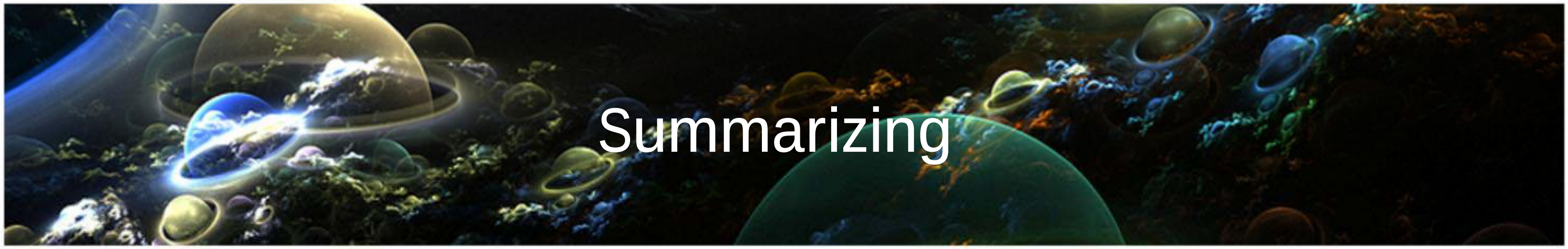
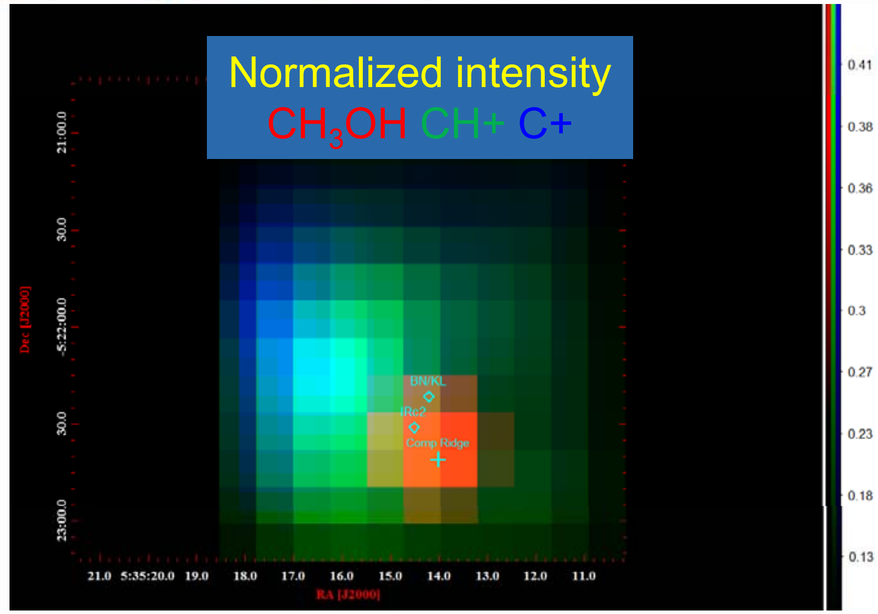
☞ Methanol and CH+ generally anti-correlate.

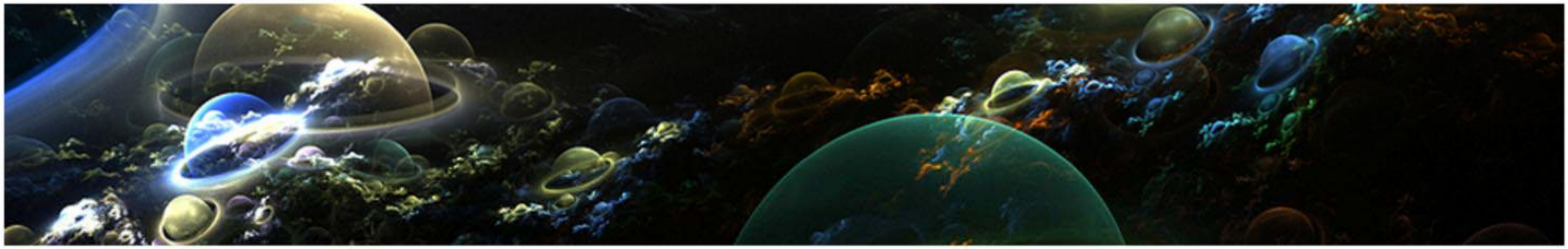


Summarizing

- C$^+$ is everywhere present in Orion KL in a clumpy distribution, several velocity components.
  – Weak around the BN/IRc2/compact ridge complex.
  – Overall consistent with KAO, ISO results.
- 13C+ multiplet lines detected
  – $^{13}C^+/^{12}C^+$ intensity ratios yield abundances in line on average with estimates around Orion Bar and θ^1 Ori C, R ≈ 55 ☞ Fractionation of $^{13}C^+$ into ^{13}CO is weak or compensated by photodissociation of ^{13}CO.
  – Variations (2σ) are noticed, we should improve τ_{12} estimates with line fitting.



- CH$^+$ is (more) smoothly distributed in intensity and velocity, **always emission**.
  – Peaks at the C+ peak, and close to θ^1 Ori C .
  – Also weak around the IRc2 complex (favors PDR formation).
  – Need to combine with CH measurements.
  – Methanol emission is significant only around the IRc2 complex, tracing highest density regions.



Congratulations SF Giants!