[^{13}CII] observations to constrain fractionation chemistry and column densities of C$^+$

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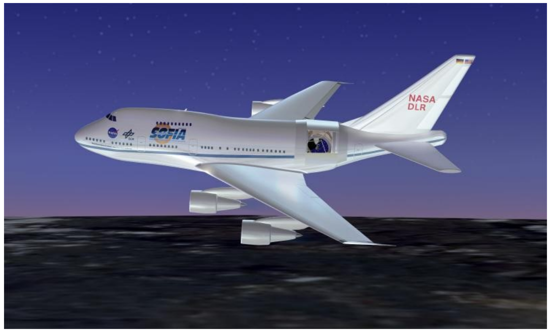
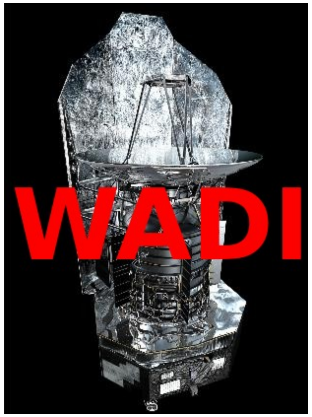
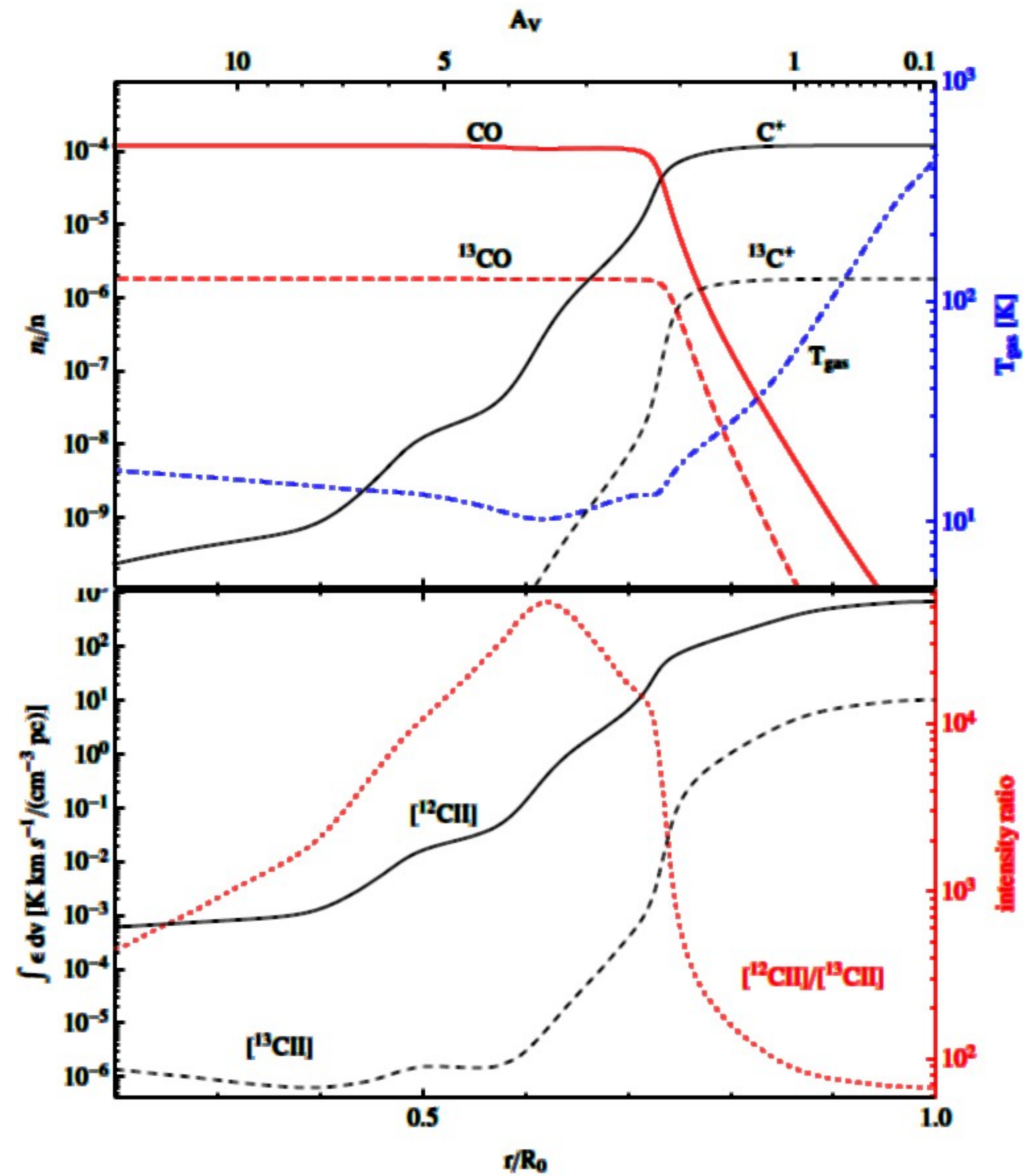




C+ as an Astronomical Tool,
Leiden, February 5, 2013

Theory

See talk by M. Röllig



Chemical structure of a spherical PDR for $\chi=1000\chi_0$

- Fractionation reaction

$$^{13}\mathrm{C}^{+} + \mathrm{CO} \rightleftharpoons \mathrm{C}^{+} + {}^{13}\mathrm{CO} + 34.8\,\mathrm{K}$$

  drives transition from C^+ to CO to different depths for ^{12}C and ^{13}C

- The $^{12}C^+/^{13}C^+$ ratio can be enhanced by factor > 100

Theory

- In most cases, the true intensity ratio is rather governed by the optical depth of the [CII] line

$$\frac{IR_\nu}{FR} = \frac{1 - \exp(-\tau_{[CII]})}{\tau_{[CII]}}$$

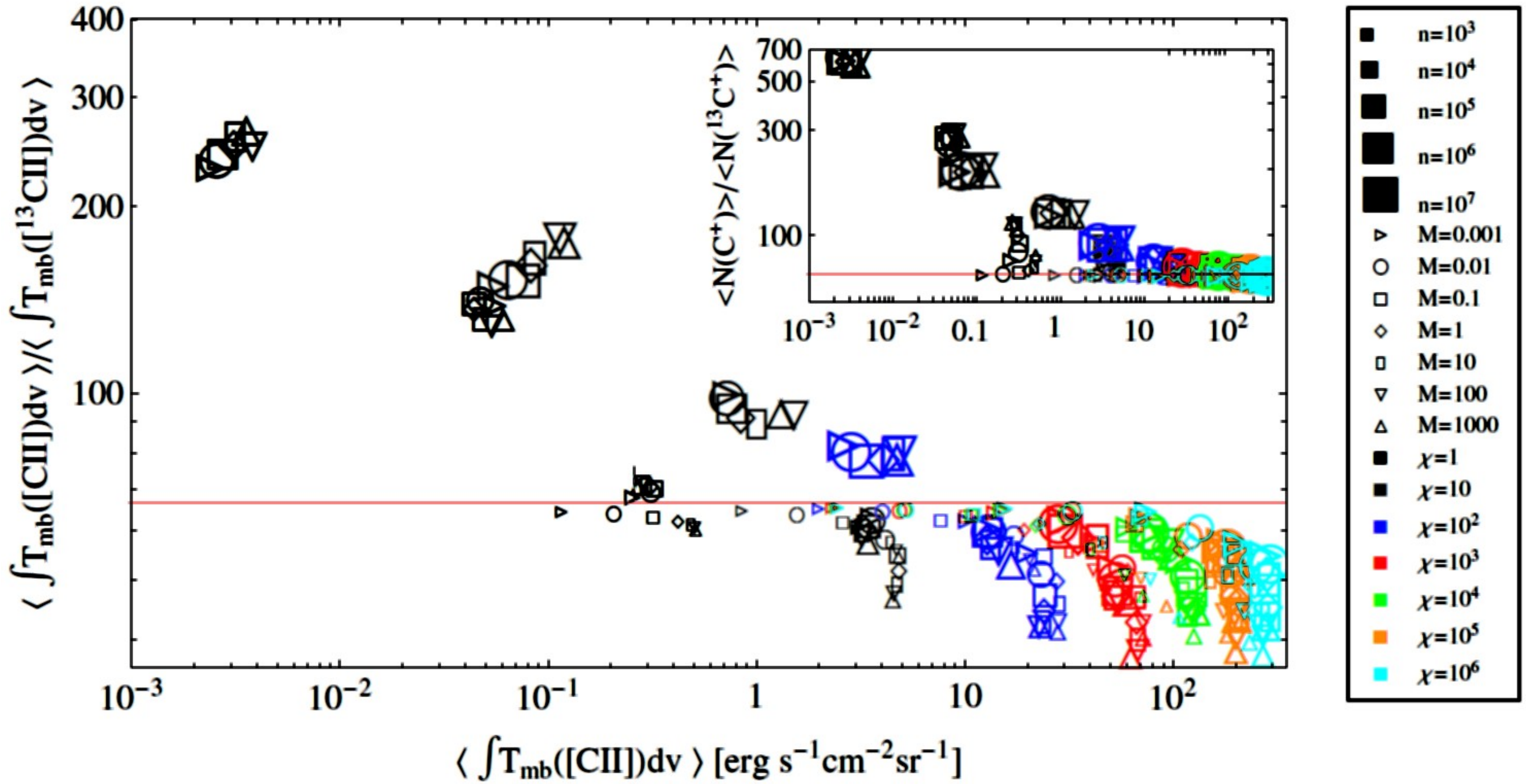
  where we assume the “standard” abundance ratio (without chemical fractionation) *FR ≈ 67* in the solar neighborhood

- If all carbon is ionized: **A_V=1 ↔ N_{C+}= 2.5 10^{17} cm^{-2} ↔ $<\tau_{[CII]}>$ = 0.8**

- [CII] turns optically thick for A_V≈1 !

Theory

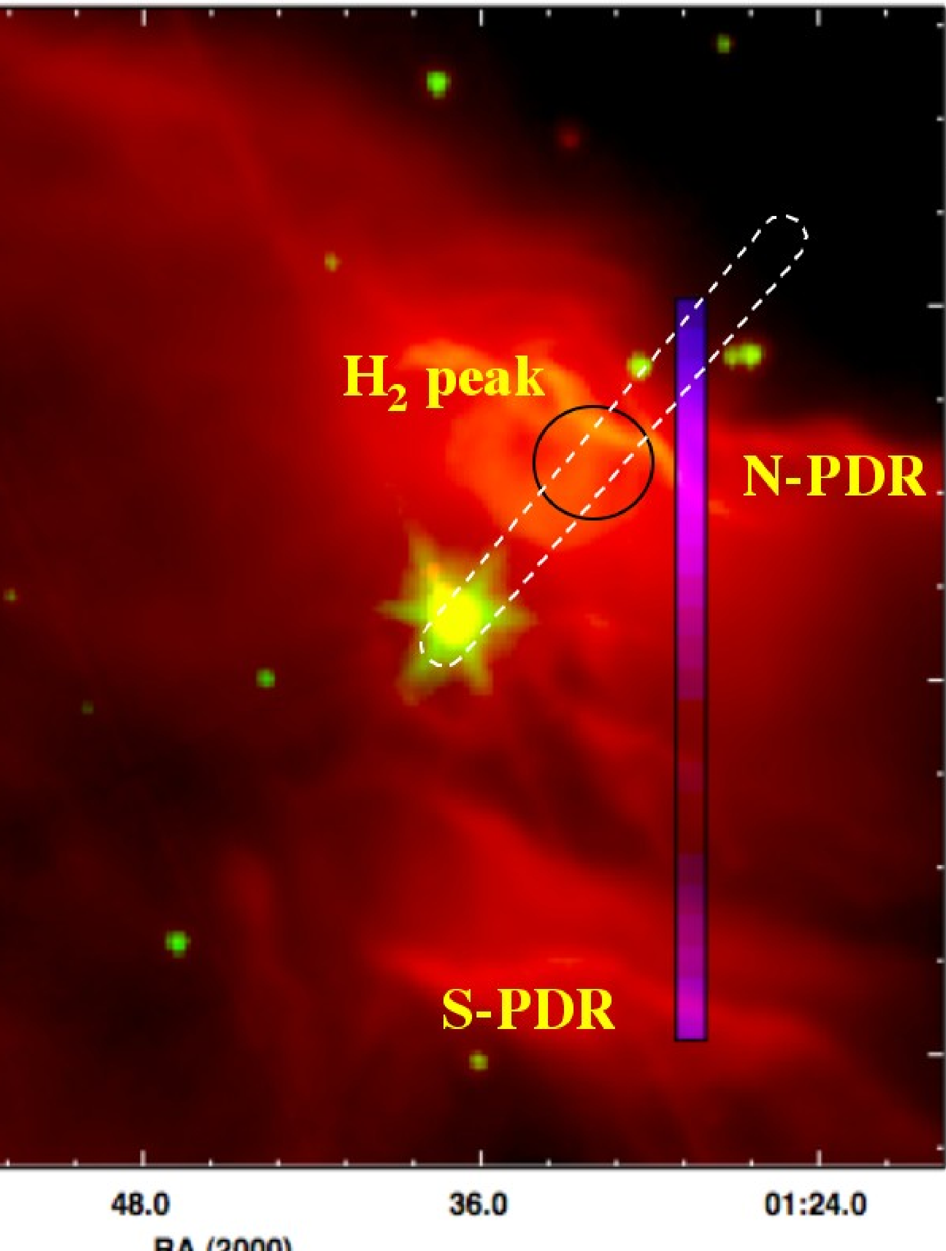
Result for spherical clouds:



Integrated [CII]/[^{13}CII] intensity ratio for spherical PDRs

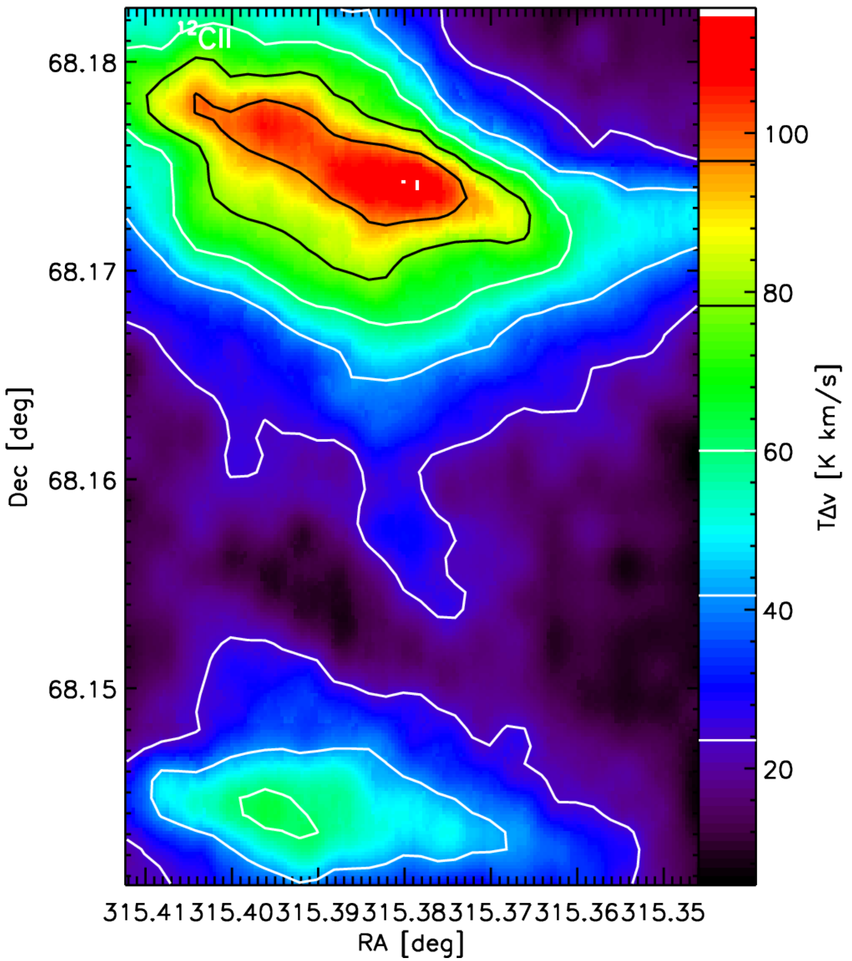
- PDRs bright in [CII] have an abundance ratio *FR* ≈ 67
- They are optically thick in [CII] → intensity ratio < 67 determined by $\tau_{[CII]}$

Observations: Case 1: NGC 7023



Spitzer IRAC (Joblin et al. 2008)

- Focus on Northern PDR (H_2-peak)



[CII] distribution (Joblin et al. in prep.)

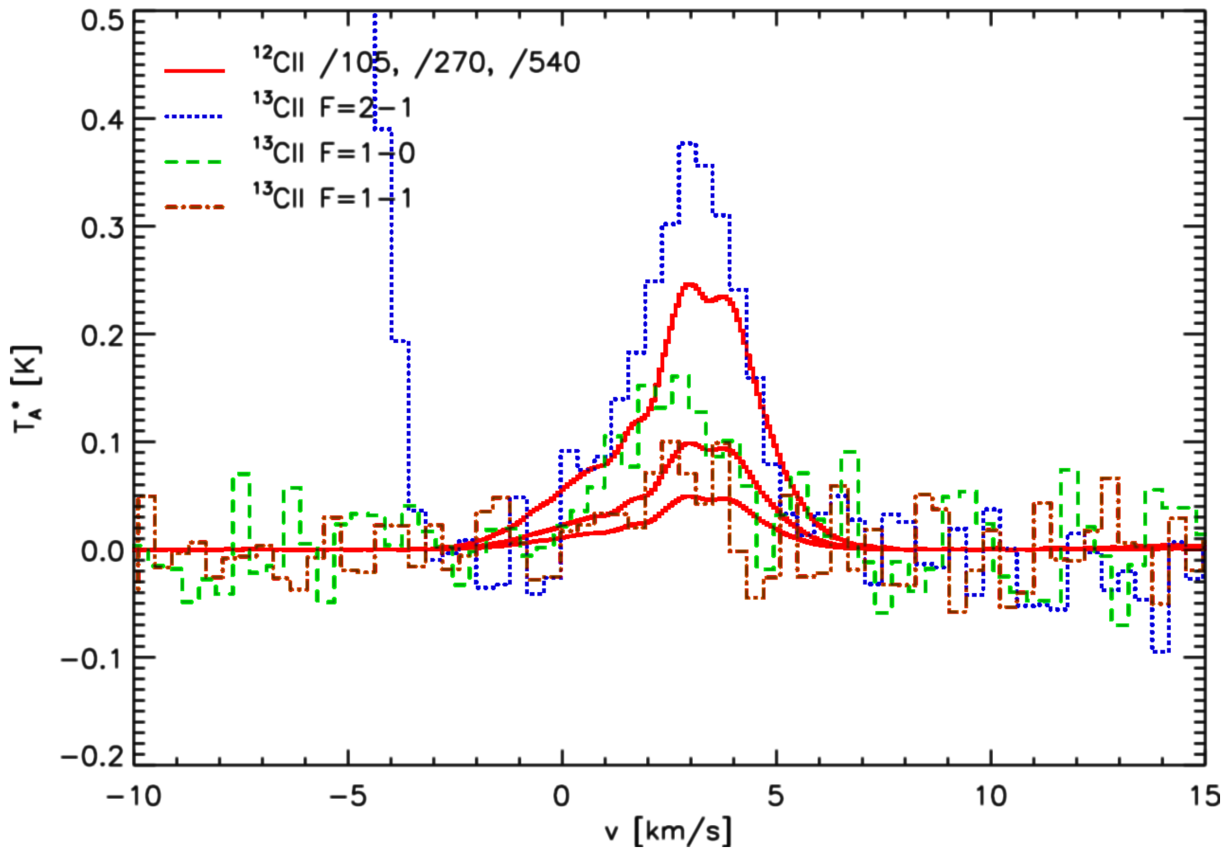
NGC 7023

[CII]:

- Self-absorption dip indicates moderate optical depth for emission in line center

[^{13}CII]:

- All 3 HF detected
- Slightly stronger than expected from [CII] and optically thin emission
- $\tau_{center} \approx 0.7$-$0.8$
- Tentative detection of enhanced *FR* in blue wing (scaled [CII] above [^{13}CII])

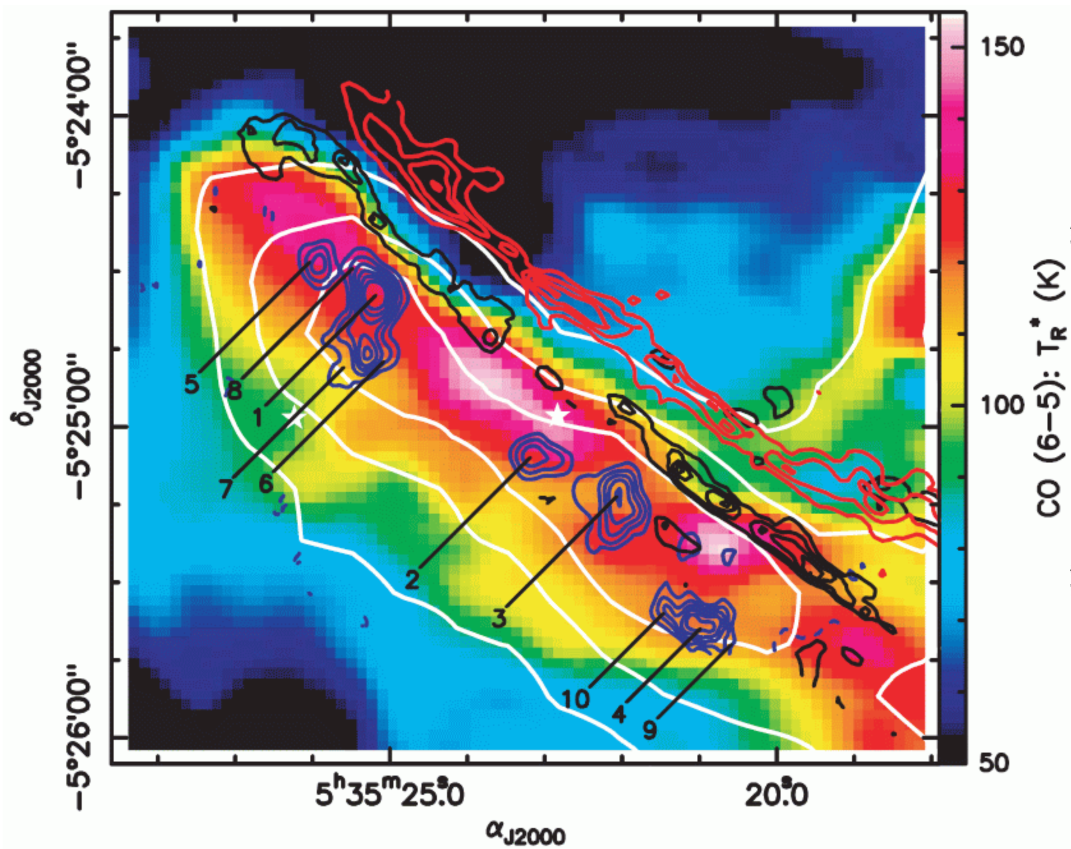


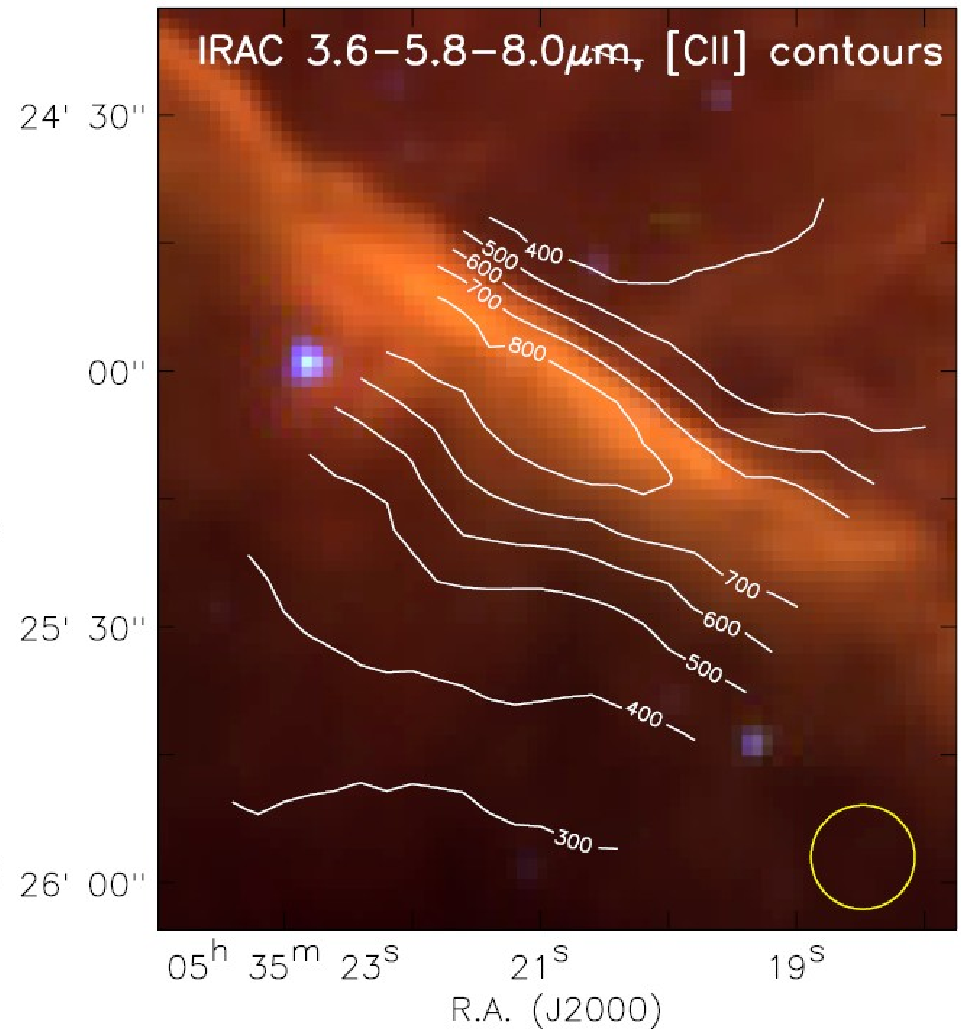
[^{13}CII] hyperfine components compared to [CII] scaled by normal HF ratio (remember the recent correction) and FR=67 for optically thin emission (Ossenkopf et al. 2013)

Case 2: The Orion Bar

Clumpy in high-density tracers, but very smooth in [CII]

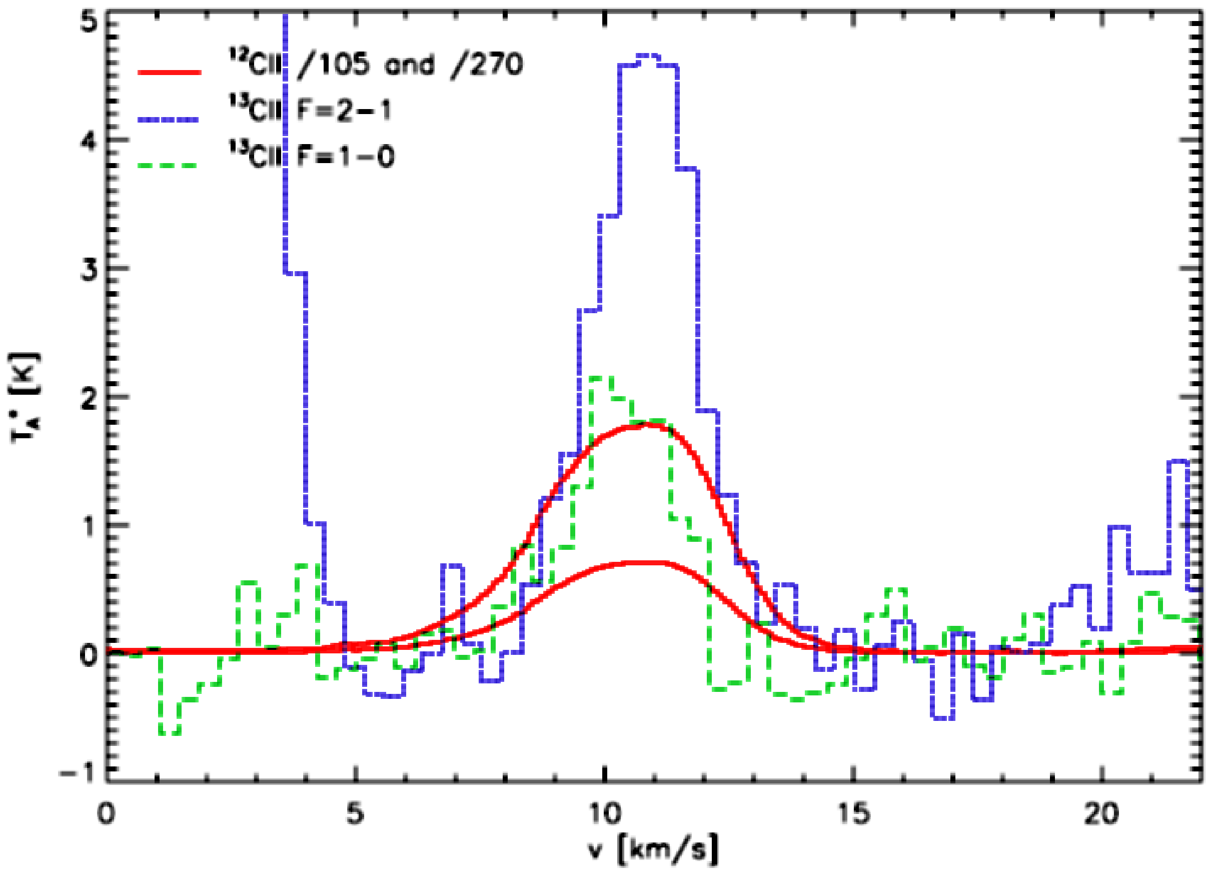
CO 6-5 (color), ^{13}CO 3-2 (white contours), OI 1.32µm (red), H_2 v=1-0 S(1) (black), $H^{13}CN$ 1-0 (blue) (Lis & Schilke 2003)





- Extremely high S/N
  (> 100 for individual channels)

[^{13}CII]

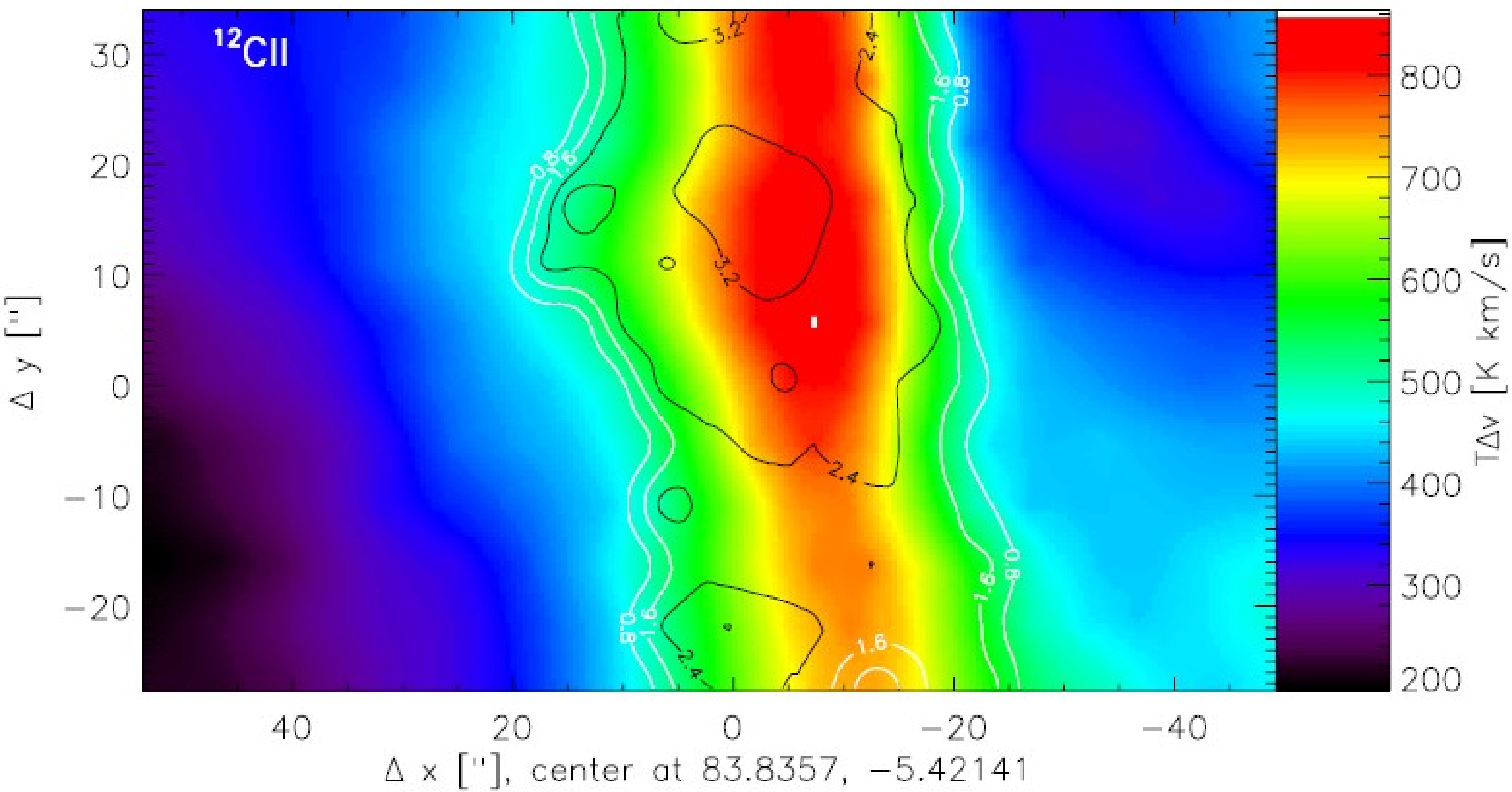


Average profile of the two strongest [^{13}CII] hyper-fine components compared to the scaled [^{12}CII] profile that would be expected from the canonical abundance ratio and optically thin lines.

- Average peak optical depth of [CII] line $\tau_{center} \approx 2.2$

Optical depth from [CII]/[^{13}CII]

Contours of the [CII] line center optical depth overlaid on integrated [CII] intensities



• Peak optical depth exceeds three at intensity maximum

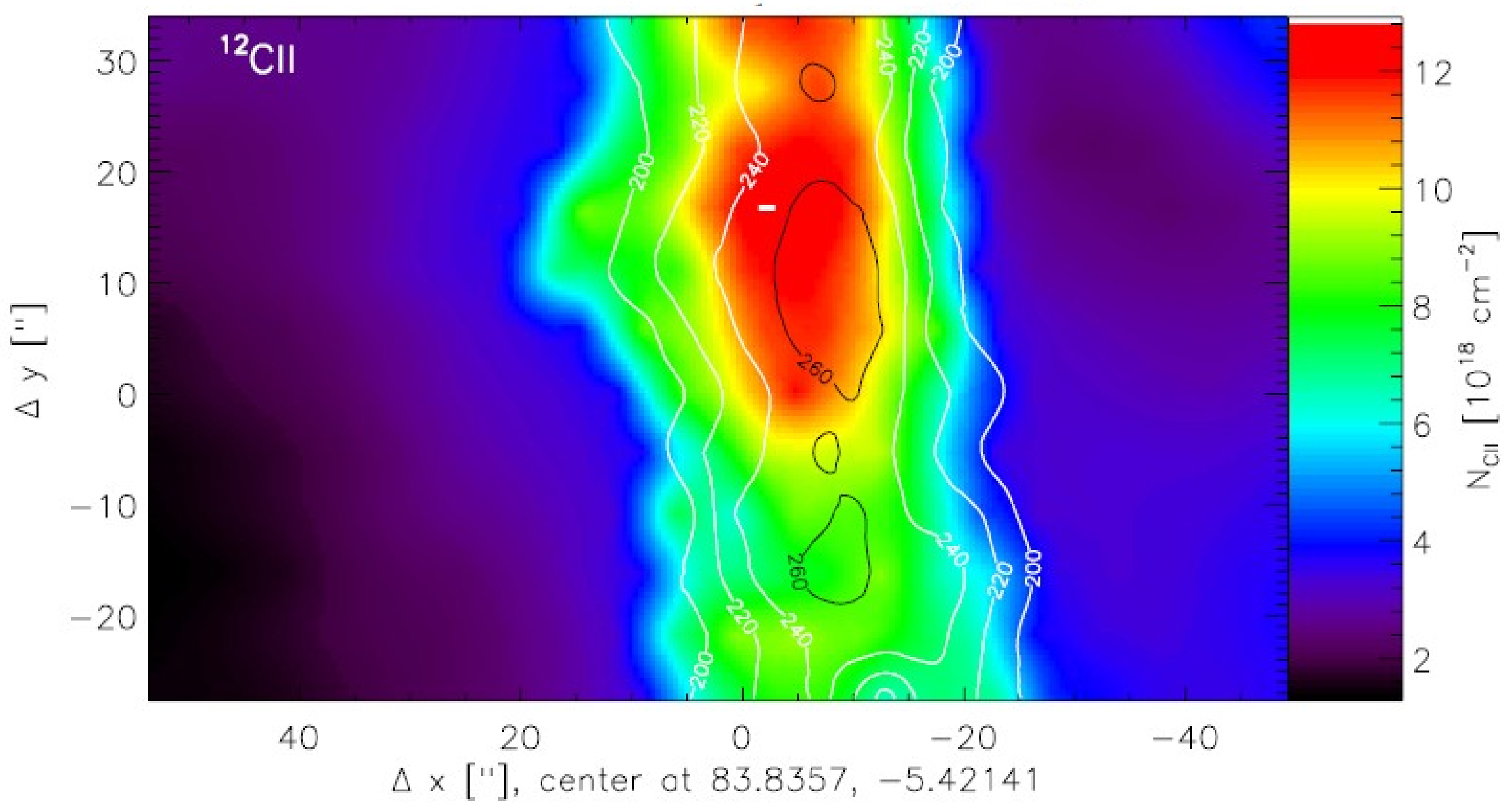
• Optical depth (= column density) layering shifted relative to intensity structure into the molecular cloud

C^+ column density

- Combine intensity and optical depth to derive C^+ column density and excitation temperature

$$\int \tau \mathrm{d}v = 7.15\times10^{-18}\,\frac{\mathrm{kms}^{-1}}{\mathrm{cm}^{-2}} \times N_{\mathrm{C}^+}\,\frac{1-\exp(-91.2\,\mathrm{K}/T_{\mathrm{ex}})}{1+2\exp(-91.2\,\mathrm{K}/T_{\mathrm{ex}})}$$

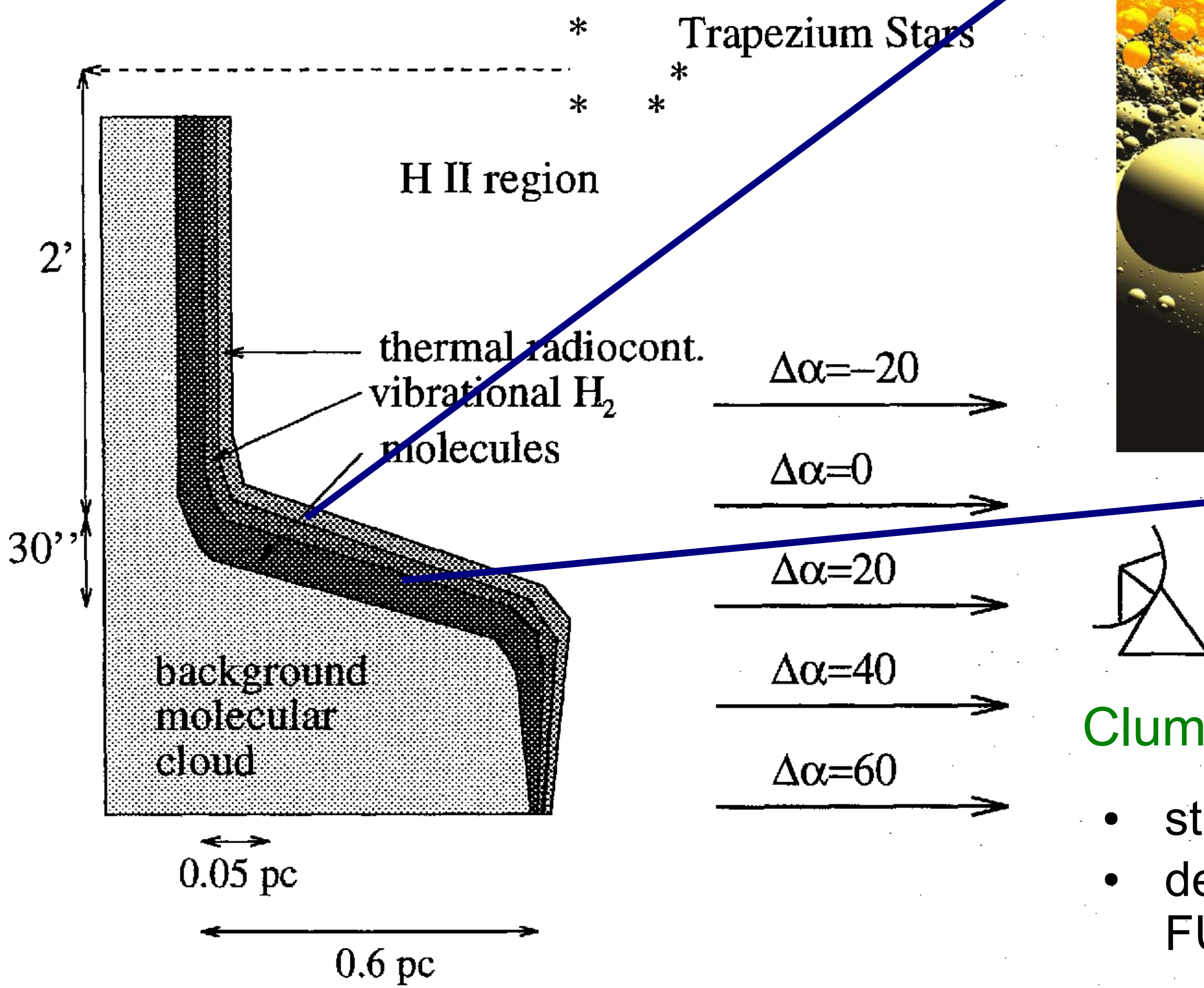
Contours of [CII] excitation temperature overlaid on the column densities.

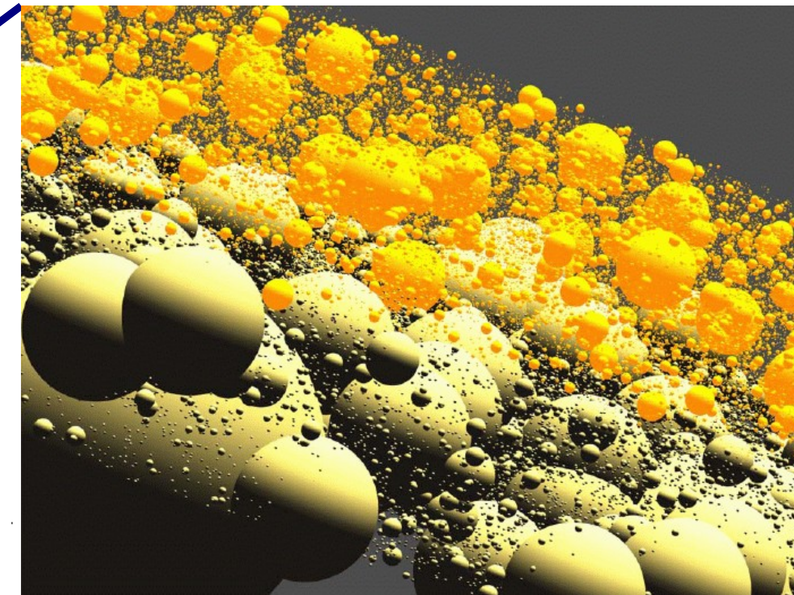


Temperature gradient in C^+ → consistent with stratification of the Orion Bar

Modeling: see poster by S. Andree

Based on Orion Bar picture from Hogerheijde et al. (1995):

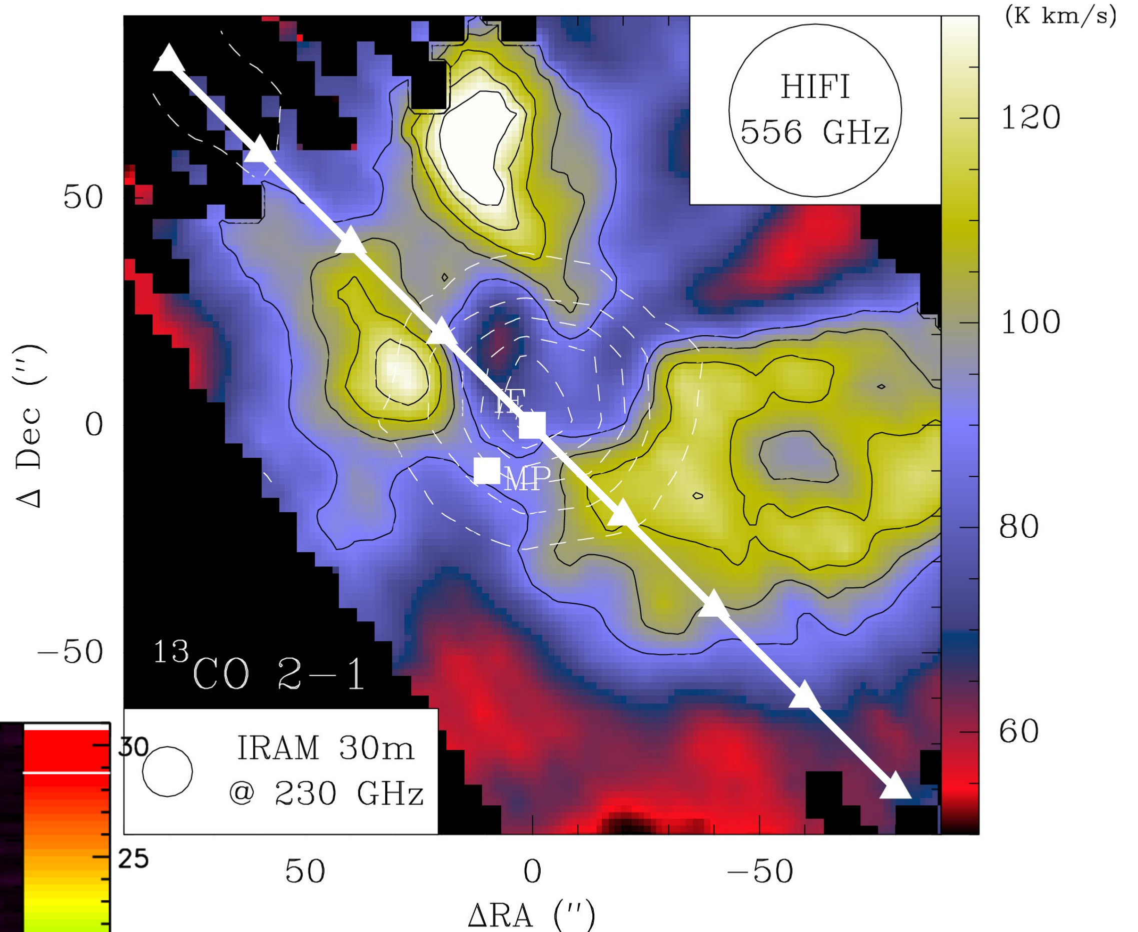




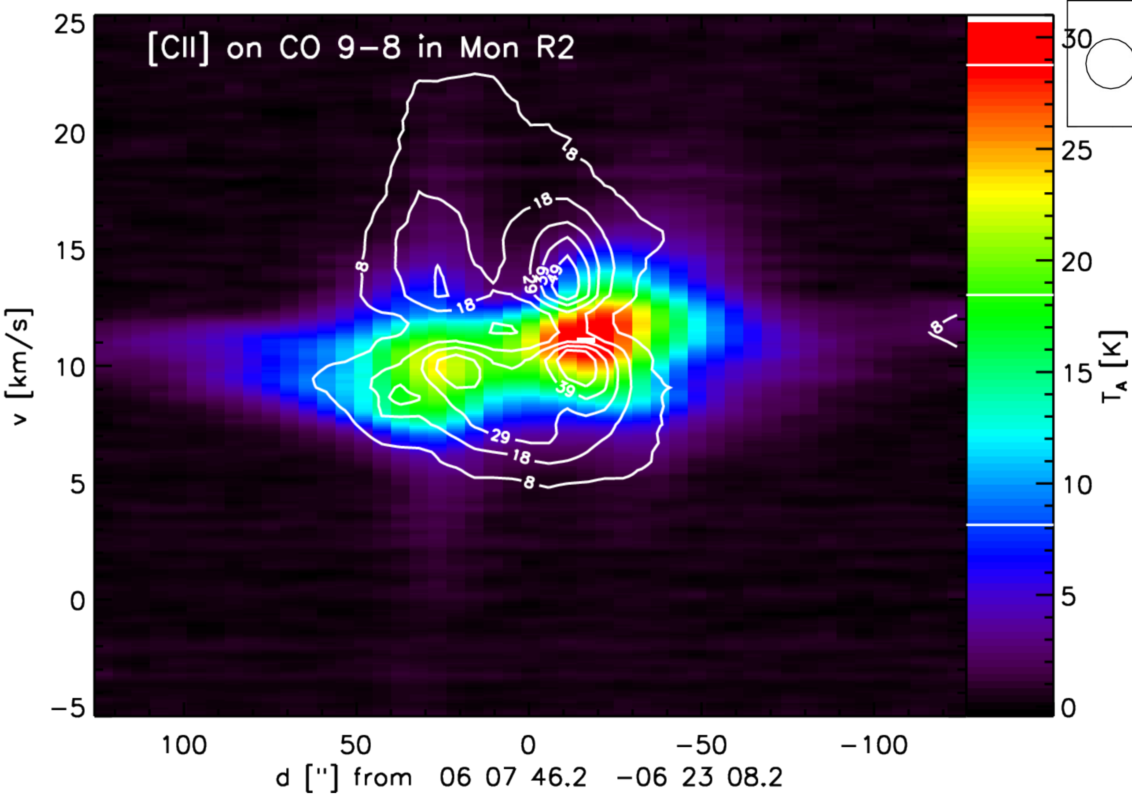
Clumpy model

- stratification of clumpy layers
- deeper layer „sees“ weaker FUV field due to attenuation

Case 3: Mon R2



Observed cut in Mon R2 overlaid on ^{13}CO 2-1 and H recombination lines (dashes) showing the HII region



p-v diagram along the cut: CO 9-8 (colors) + [CII] (contours)

- Broad wings and double-peak structure of [CII] profiles

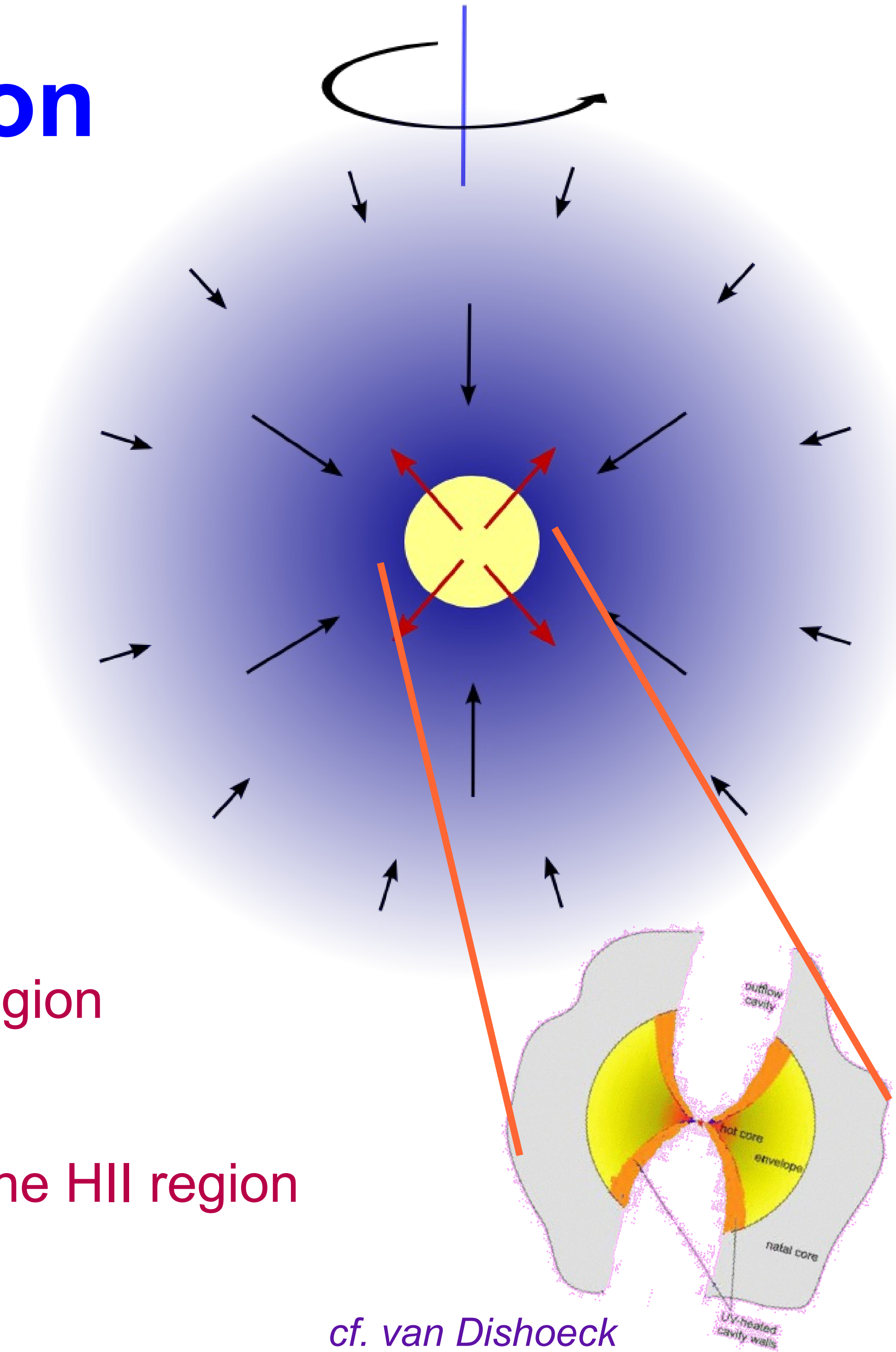
Interpretation

- Large-scale infalling cloud
  - Increasing density
  - Accelerated infall
  - Large-scale rotation

- Expanding walls of HII region
  - Harbors bipolar outflow

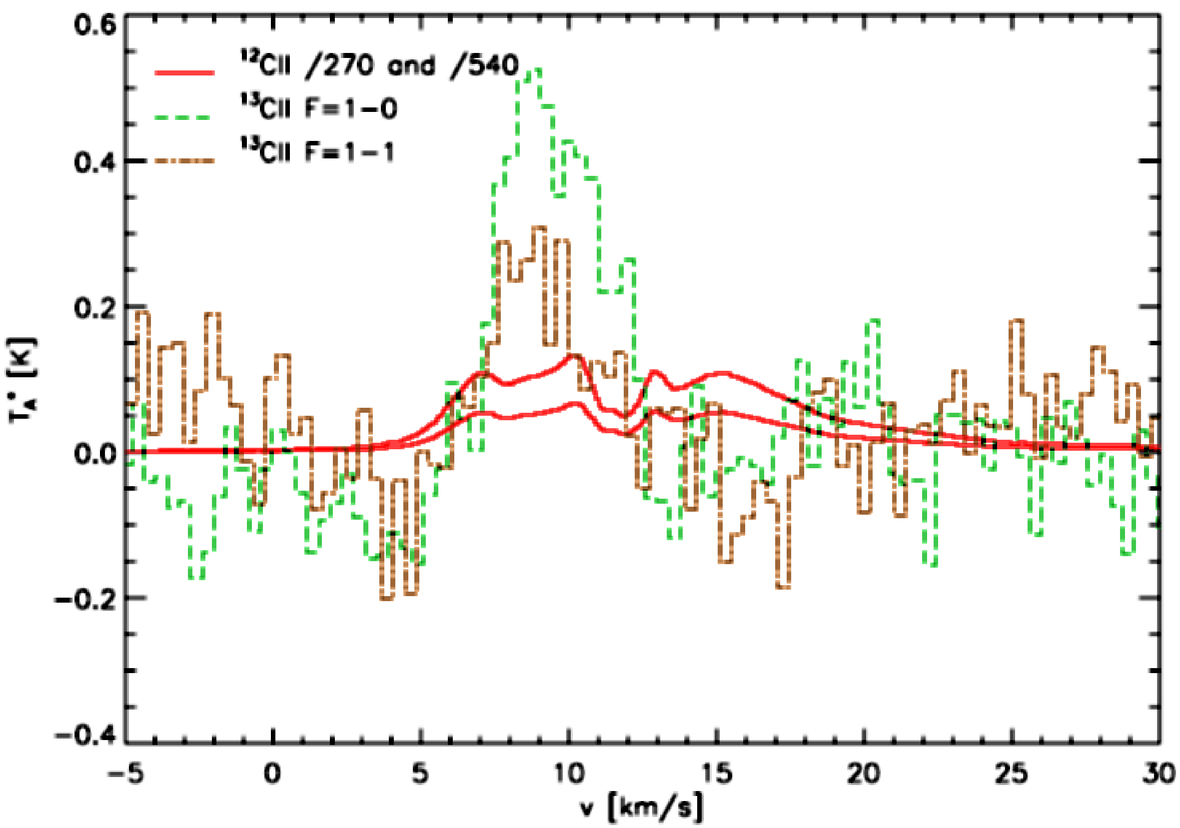
→ [CII] mainly from walls of HII region

  - Wings trace ionized flow
  - Some self-absorption in the HII region



cf. van Dishoeck

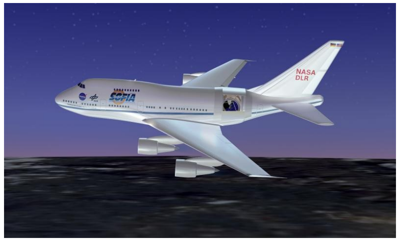
[^{13}CII]



Comparison of the profiles of the [^{13}CII] hyperfine lines in Mon R2 with the scaled [CII] profiles from the same position.

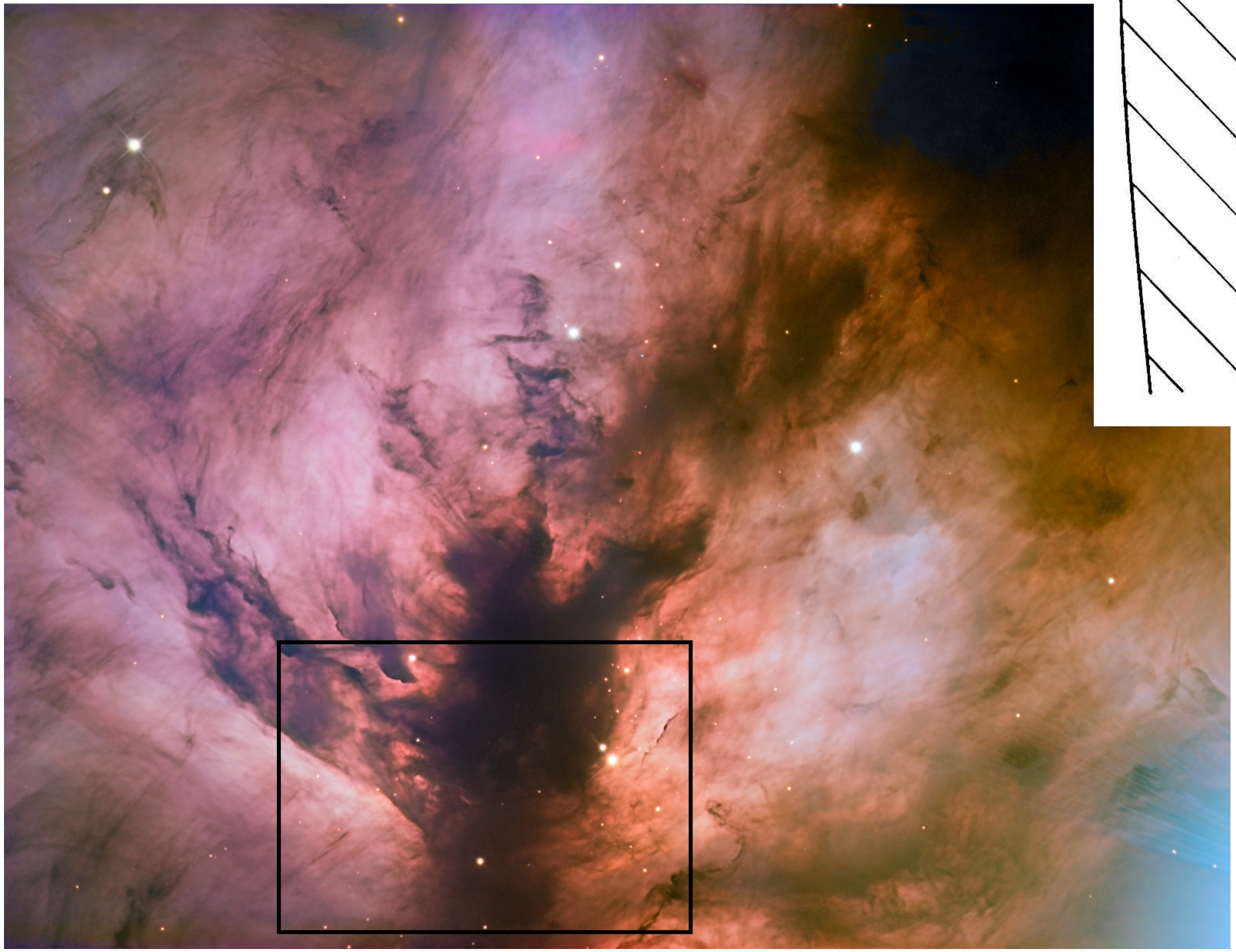
The blue-shifted [^{13}CII] component is enhanced by factor 3 → **$\tau_{[CII]}$ > 3**

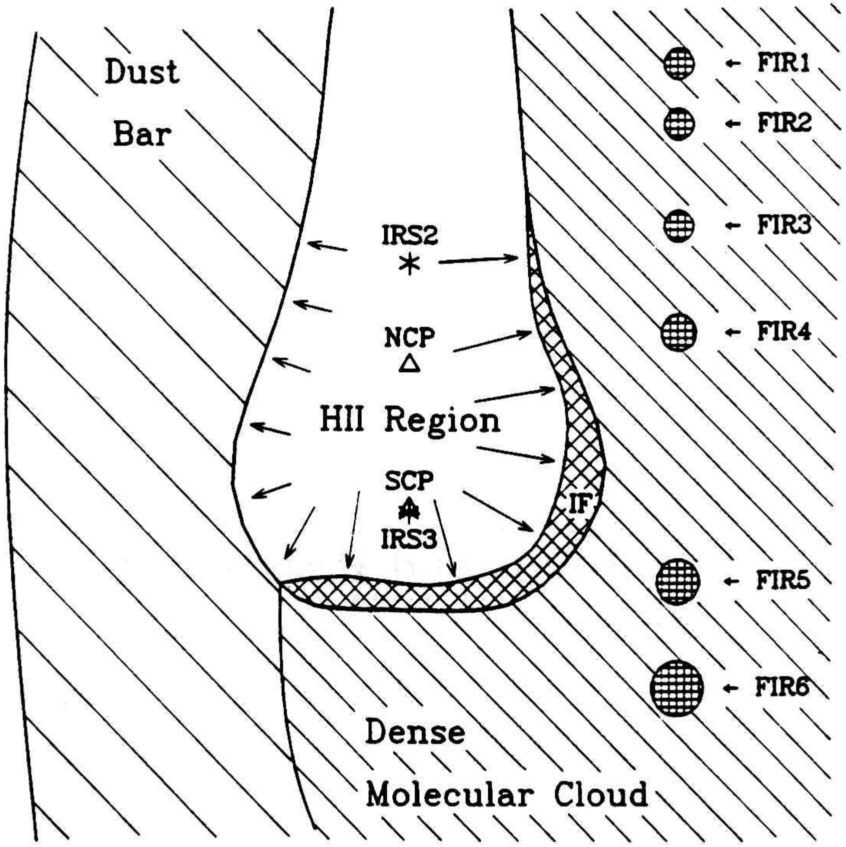
- **But: non-detection of the red component in [^{13}CII]**
  - First observation of $^{13}C^+$ fractionation in a PDR ?
  - But [CI] also shows only the blue component



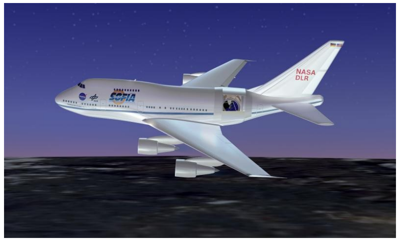
Case 4: NGC2024

Optical image with mapped region

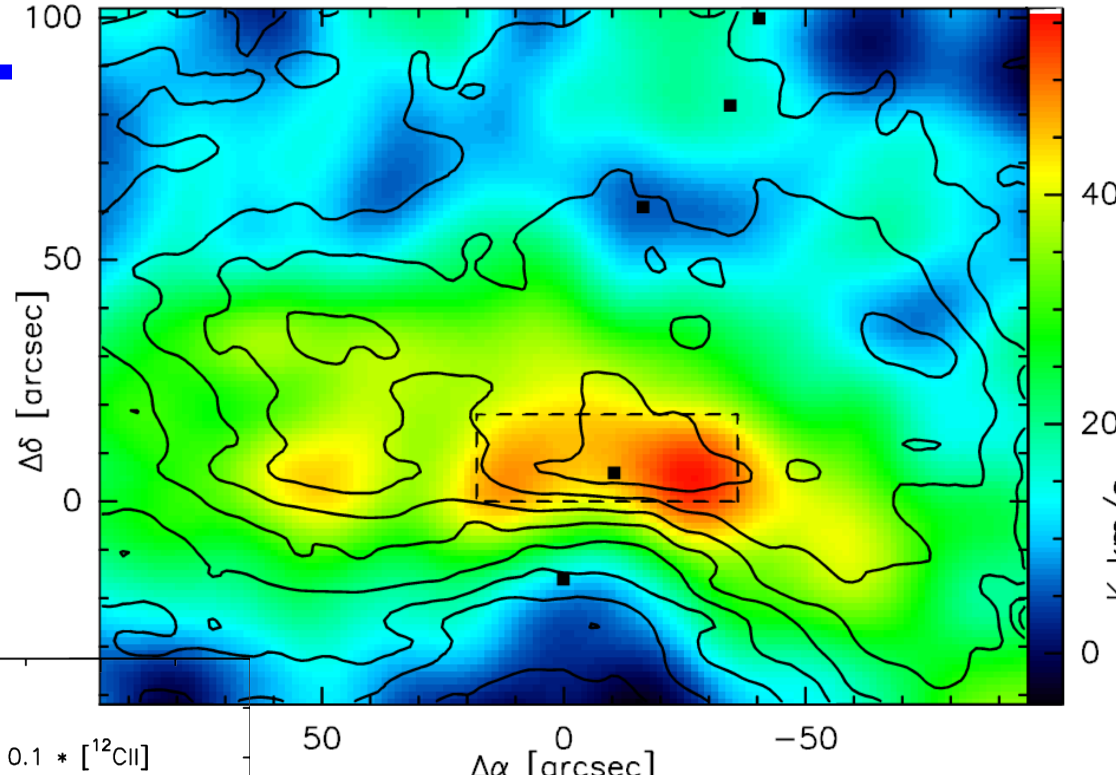




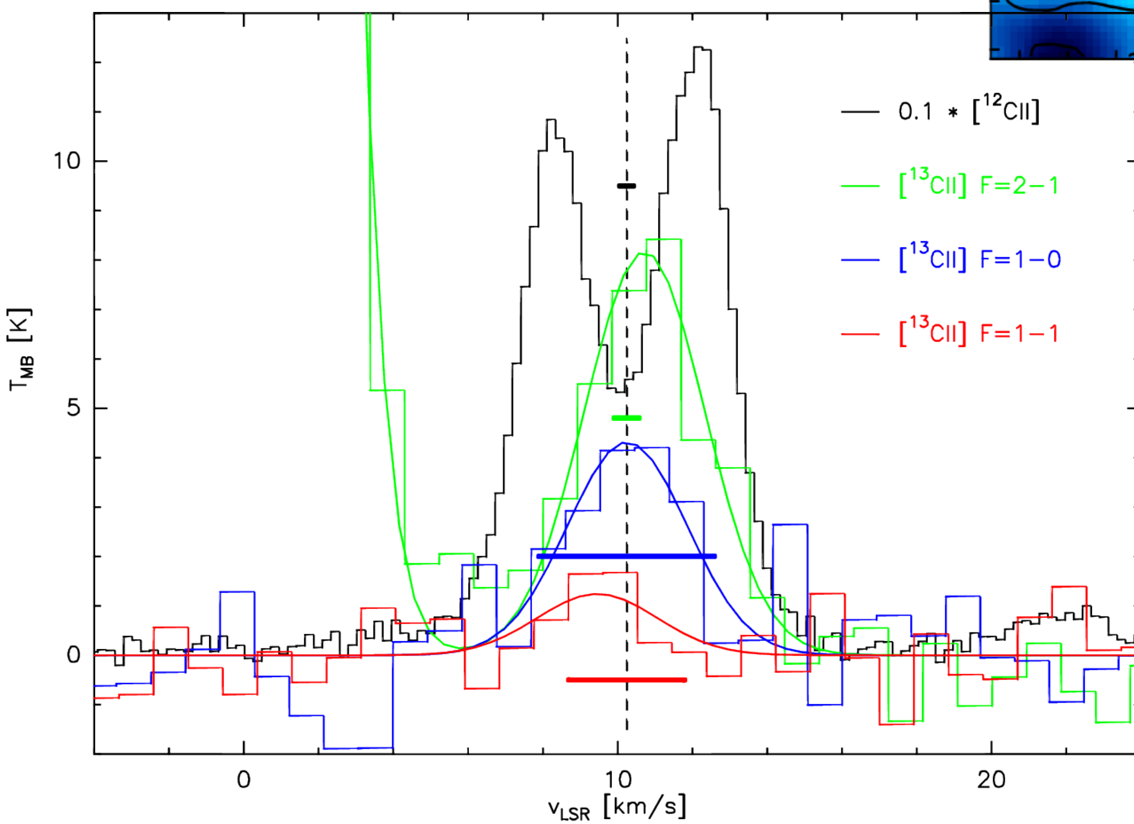
Structure of the source:
The HII region expands into an inhomogeneous medium with a denser hotter PDR in the back (Graf et al. 1993)



$[^{13}CII]$ vs. [CII]

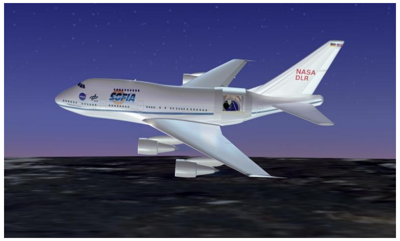


Integrated intensities of [CII] (contours) and $[^{13}CII]$ (colors)

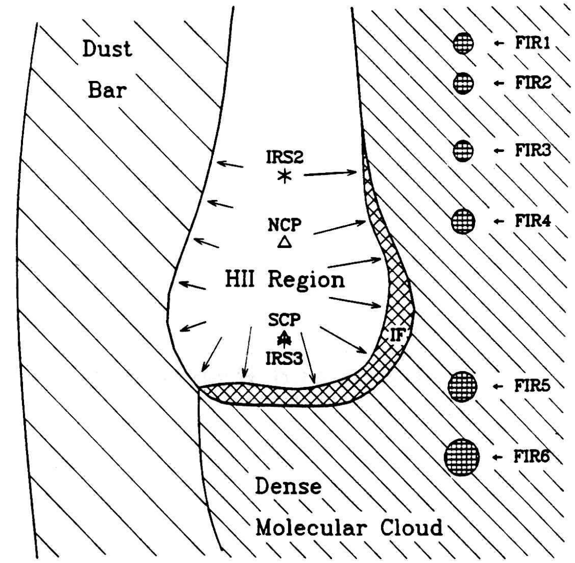


Comparison of the average profiles of the $[^{13}CII]$ hyperfine lines in NGC2024 with a scaled [CII] profile (Graf et al. 2012).

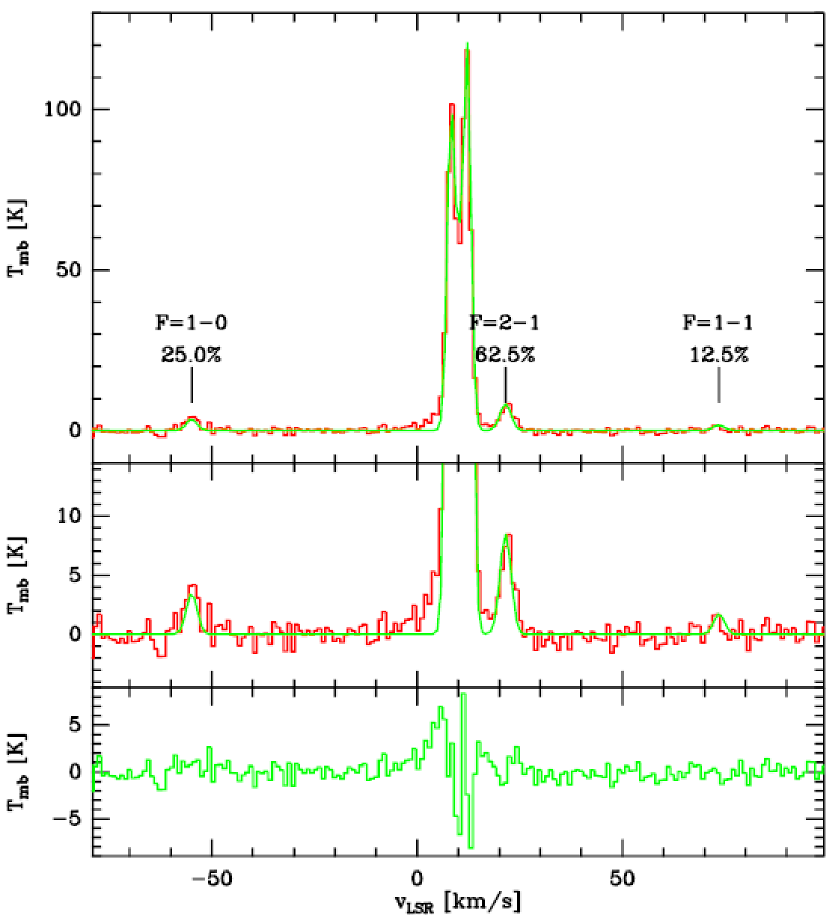
- Deep self-absorption in [CII]
  → High foreground optical depth

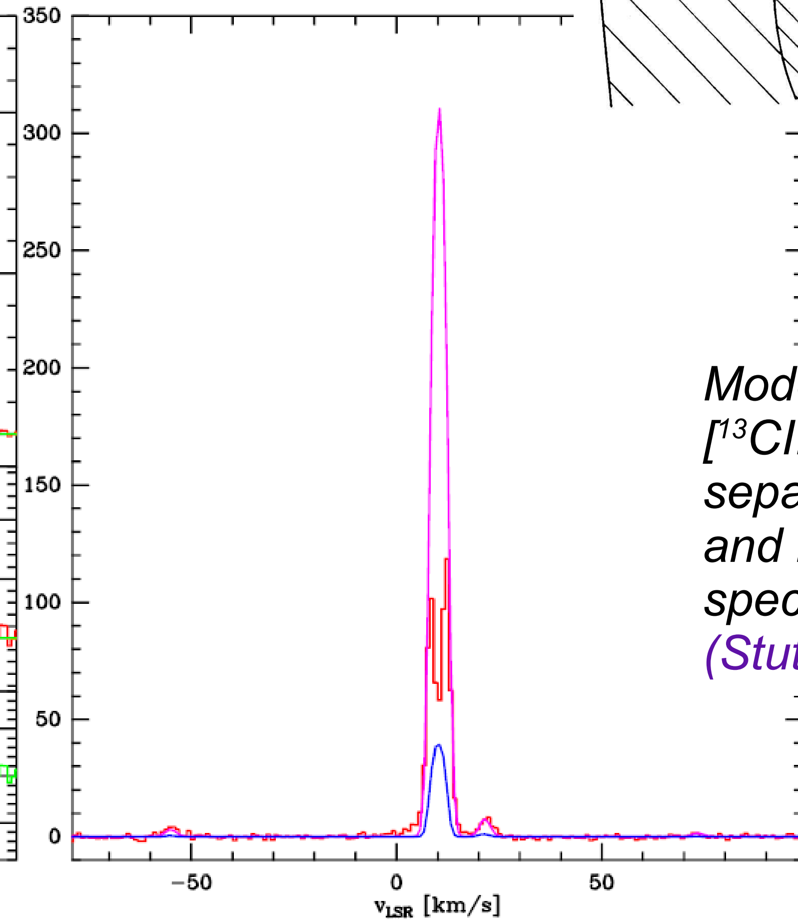


Modelling



Background: N(C^+) = 1.0 10^{19} cm^{-2}, T_{ex} = 400 K
Foreground: N(C^+) = 2.4 10^{18} cm^{-2}, T_{ex} = 80 K





Model fit to [CII] and [^{13}CII] lines (left) and separate foreground and background [CII] spectra (right)
(Stutzki et al. 2013)

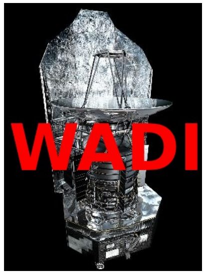
→ Very high C^+ column density required

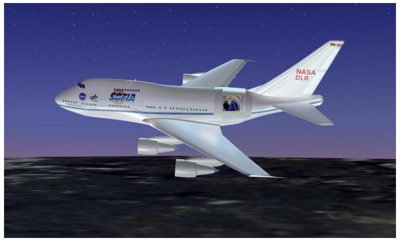
Column densities

Other sources:

Source	Integration range [km s^{-1}]	[C II] [K km s^{-1}]	IR[a]	$\langle\tau_{[CII]}\rangle$	N_{C^+}[b] [10^{18} cm^{-2}]
Orion Bar, peak	7–13	857 ± 5	30 ± 2	1.9 ± 0.2	10.1
Orion Bar, ridge[c]	7–13	772 ± 5	38 ± 3	1.3 ± 0.2	7.2
Orion Bar, front[d]	7–13	506 ± 7	69 ± 12	0.0 ± 0.4	2.3
Orion Bar, back[e]	7–13	529 ± 6	50 ± 6	0.7 ± 0.3	3.9
Mon R2, total	5–25	362 ± 5	38 ± 10	1.3 ± 0.6	5.7
Mon R2, blue	5–12.5	173 ± 3	20 ± 5	3.2 ± 0.8	4.8
Mon R2, red	12.5–25	188 ± 4	170 ± 120	0.0 ± 0.5	0.9
NGC 3603	10 – –19	130 ± 2	25 ± 5	2.4 ± 0.4	3.6
NGC 7023	–1–7	91 ± 2	51 ± 6	0.6 ± 0.3	1.0

- **C^+ column densities consistent with known gas column assuming C/H=1.2 10^{-4}, but all carbon being in ionized form!**





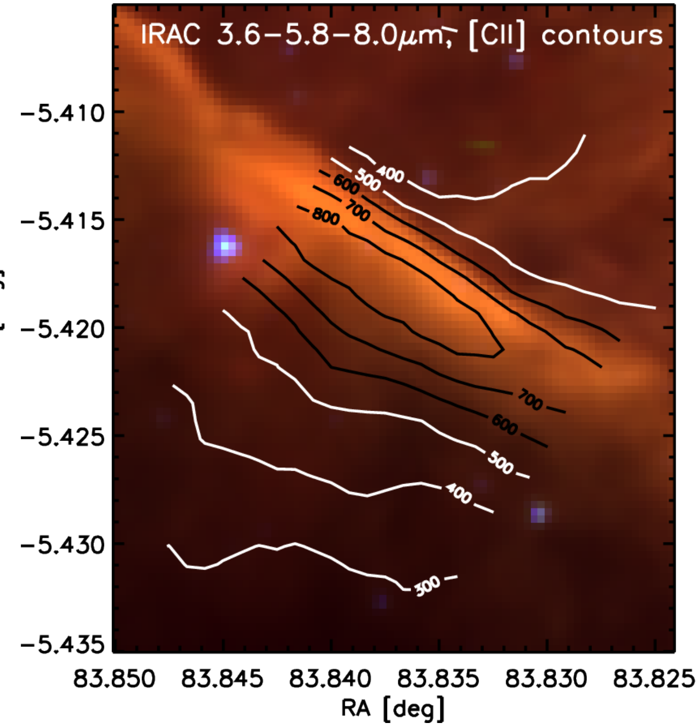
Summary

- [CII] very extended
  - Emission broad in space and velocity space
  - Very smooth emission structure across the Orion Bar
  - Origin probably mainly in a diffuse gas component

- Indications for carbon fractionation, i.e. enhanced [CII]/[^{13}CII] in few velocity components, in particular the red component of MonR2

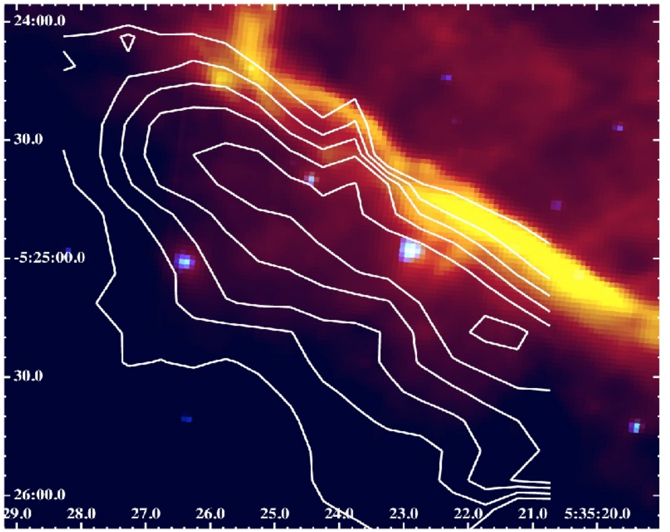
- Where detected [^{13}CII] allows to measure actual C^+ column density
  - Large columns in all sources
  - **Too large ?**

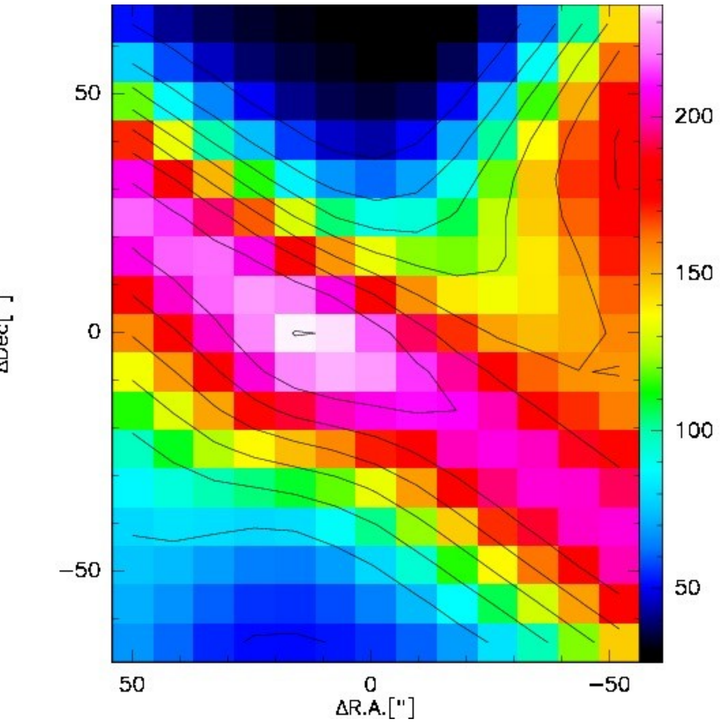
Compare spatial structure



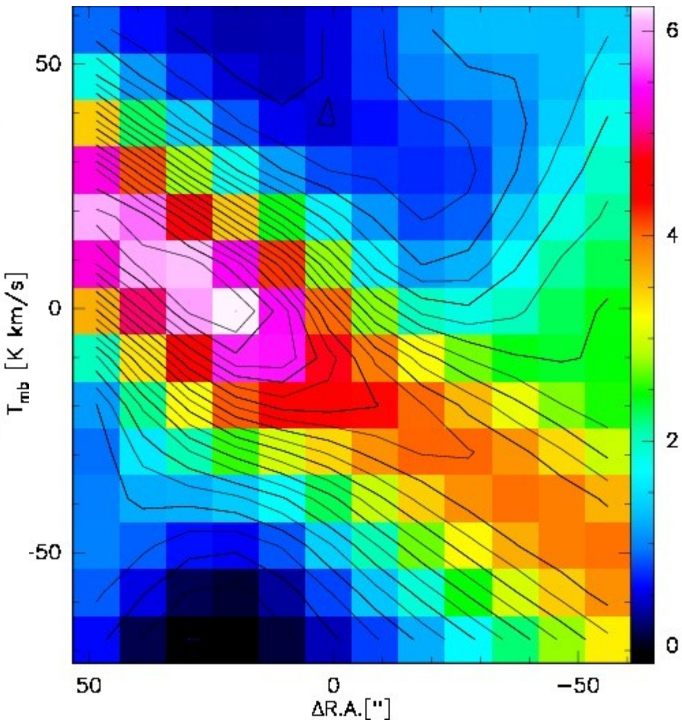
[CII]

^{13}CO 3-2

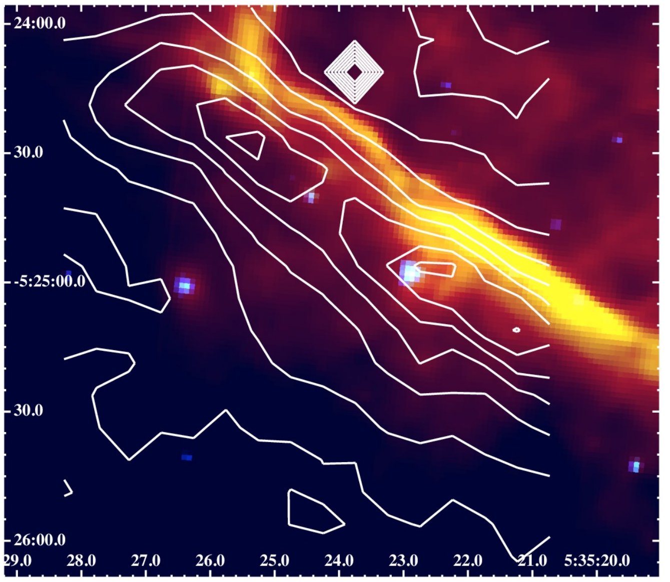




CO 10-9



$C^{18}O$ 9-8



C_2H (v.d. Wiel et al. 2010)

- Best correlation with C_2H

[CII]

- Very smooth structure
  - No clumpiness in [CII]
  - Similar to MIR

FORECAST: 19.7 and 37μm

(Shuping et al. 2012)