PDR dynamics from pv-diagrams

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Köln, December 20, 2011

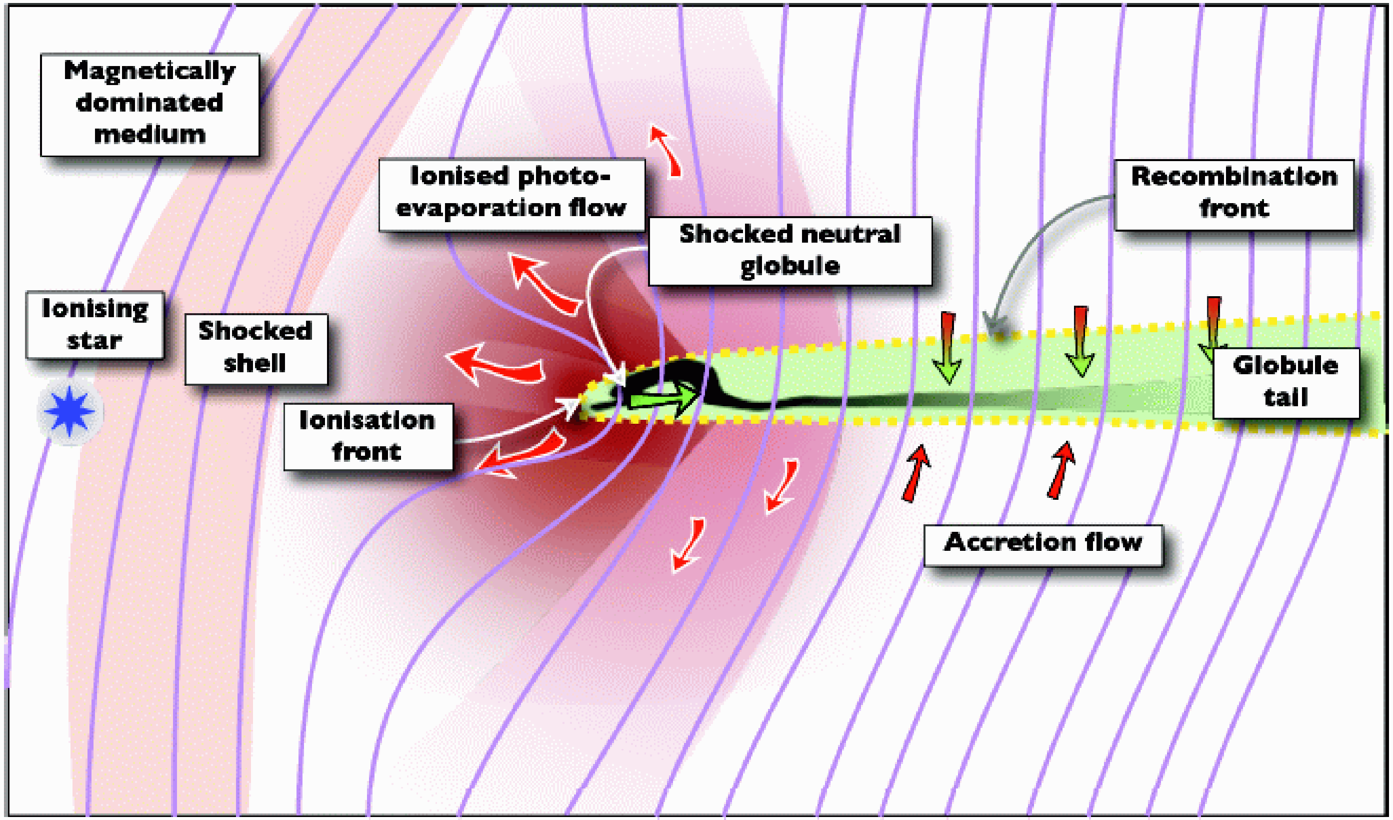
What do we expect?

Dynamics and kinematics:

- Photo-evaporation of PDRs dominates flow of ionized material
- High pressure zone at PDR surface → cloud compression
  → shock fronts
- Ionization front "eats" into molecular cloud

→ pillar formation

- Advection flows
- Unknown impact of turbulence



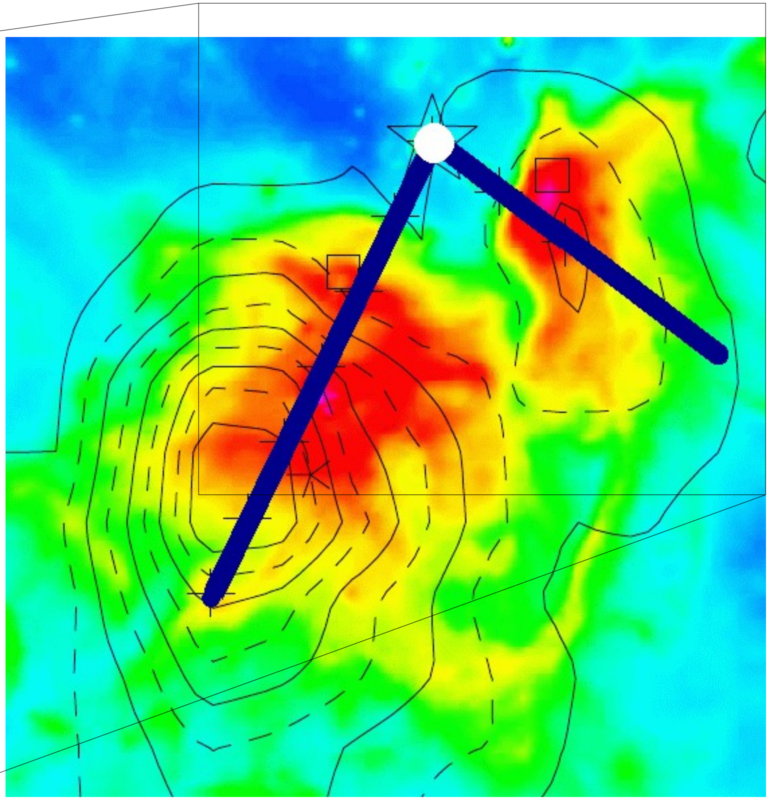
3-D MHD model by Henney et al. (2009)

HIFI Observations

Measure layering structure - example: NGC3603

- cuts across the interfaces of PDRs and shock regions
- deep integrations at selected positions for rare species

Pillars at PDR fronts (HST, Brandner et al. 2000)



Observed cuts overlaid on Spitzer 8µm (color) and CO 4-3 (contours)

Summary

species	[CII]	CO	^{13}CO	HCO^+	CH	CH^+	C_2H	H_2O	H_2O
frequency [GHz]	1901	1037	1101	535	537	835	524	1113	557
NGC3603 MM1	40.4	12.8	2.61	0.54	0.48	0.64[a]	0.41	0.43	0.46
NGC3603 MM2	44.0	11.3	2.69	0.47	0.51	0.60[a]	0.30	0.39	0.45
MonR2	62.7	32.8	10.4	4.55	1.10	1.31	1.04	1.05	1.04
S140	23.8	25.9	7.71	7.44	0.69	0.39[a,r]	0.89	2.55	2.48[a]
Carina N	63.6	16.3	3.19	0.87	0.82	<0.1[a]	0.49	<0.15	0.16[a]
Carina S	9.82	3.48	<0.1	0.09	<0.05	<0.1[a]	<0.03	<0.15	<0.02[a]
NGC7023 N	33.6	19.9	3.46	0.27	0.71	0.37	0.11	<0.15	0.12[a]
NGC7023 C	33.1	14	-	0.27	0.7	-	0.11	-	0.12[a]
NGC7023 E	13.8	3.93	<0.1	<0.07	0.09[m]	<0.03[a]	<0.05	<0.1	<0.02[a]
Rosette N	5.92	2.36	<0.3	0.14	0.18	<0.07[a]	<0.07	<0.3	<0.03[a]
Rosette S	5.3	<0.5	<0.3	<0.03	<0.1	<0.07[a]	<0.07	<0.3	0.04[a]
Horsehead	13.5	2.62	-	0.16	0.26	<0.1[a]	<0.03	-	0.09[a]
Ced 201	5.82	<0.15[a]	<0.03[a]	<0.03[a]	<0.03[a]	<0.15[a]	<0.03[a]	<0.03[a]	0.02[a,m]

species	H_2CO	CS	SO	SH^+	NH_3	N_2H^+
frequency [GHz]	526	539	560	526	572	559
NGC3603 MM1	<0.07	<0.07	<0.1	<0.07	0.13	<0.07
NGC3603 MM2	<0.07	0.09[m]	<0.1	<0.07	0.13	<0.1
MonR2	0.31	0.38	0.31	<0.03	1.02	1.21
S140	0.52	0.36	0.38[a]	<0.03	1.56[a]	1.22[a]
Carina N	0.14[m]	<0.03	<0.02[a]	<0.03	0.08[a]	<0.02[a]
Carina S	<0.03	<0.03	<0.02[a]	<0.03	<0.02[a]	<0.02[a]
NGC7023 N	<0.03	<0.03	<0.03[a]	0.08	0.05[a]	<0.03[a]
NGC7023 C	<0.03	<0.03	<0.03[a]	0.06	0.05[a]	<0.03[a]
NGC7023 E	<0.03	0.05[m]	<0.02[a]	<0.05	<0.02[a]	<0.02[a]
Rosette N	<0.07	<0.03	<0.03[a]	<0.05	<0.03[a]	<0.03[a]
Rosette S	<0.07	<0.07	<0.03[a]	<0.05	<0.03[a]	<0.03[a]
Horsehead	<0.02	<0.02	<0.01	<0.02	0.02	0.01[a,m]
Ced 201	<0.03[a]	<0.03[a]	<0.02[a]	<0.03[a]	<0.02[a]	<0.02[a]

(a) Only single point on stripe observed, no OTF map.

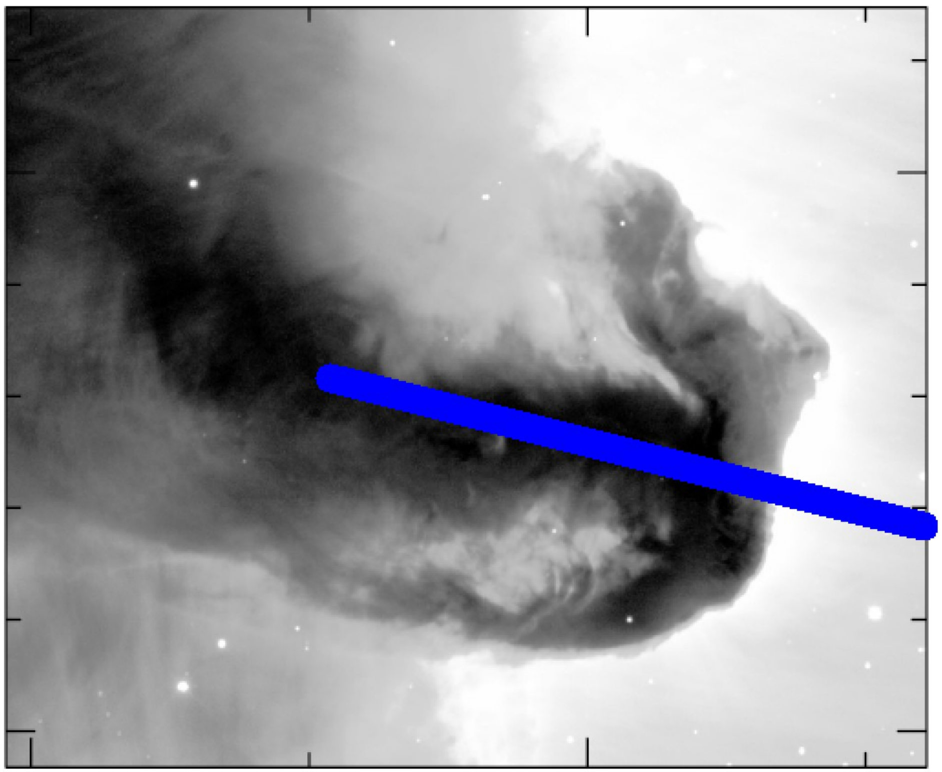
(m) Marginal/tentative detection.

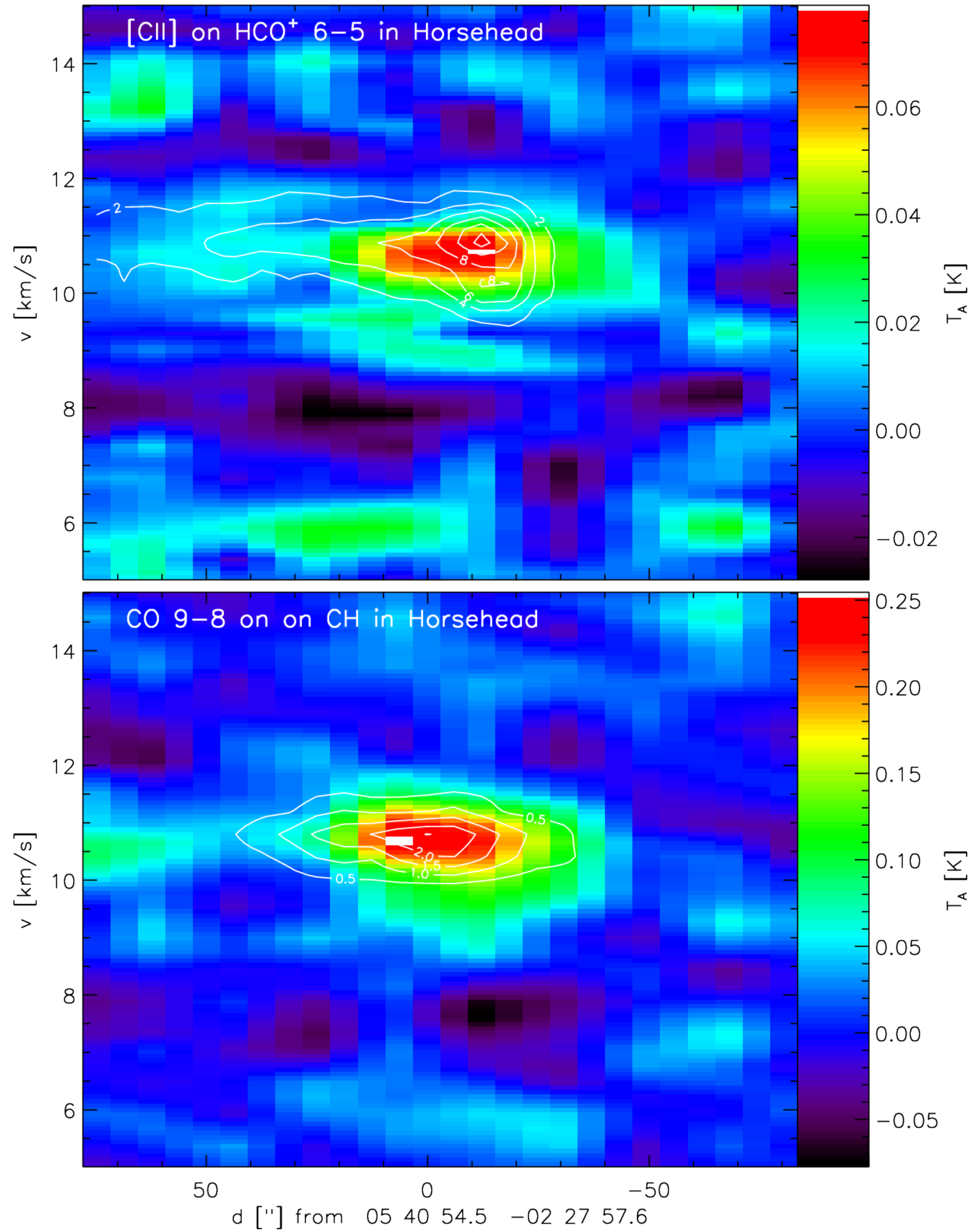
(r) Emission above absorption trunk of 0.27 K.

Summary of the HIFI mapping data. Numbers give the peak T_A^* in Kelvin for the considered stripe and transition.

Example 1: Horsehead

Measure layering structure –
p-v diagrams:

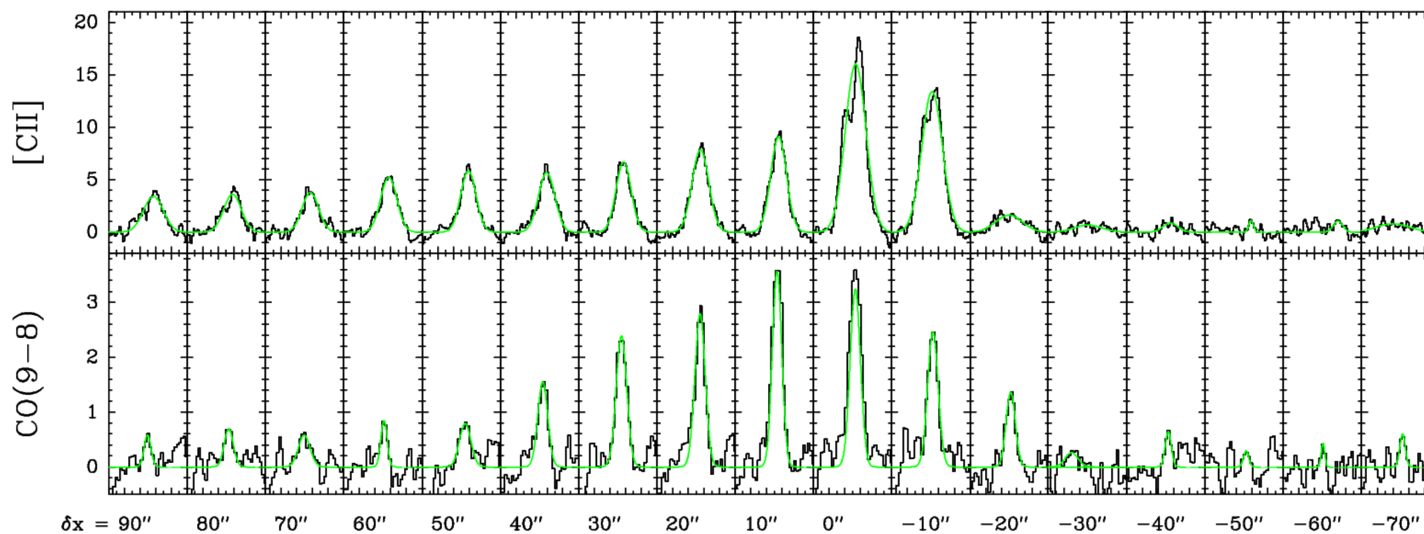




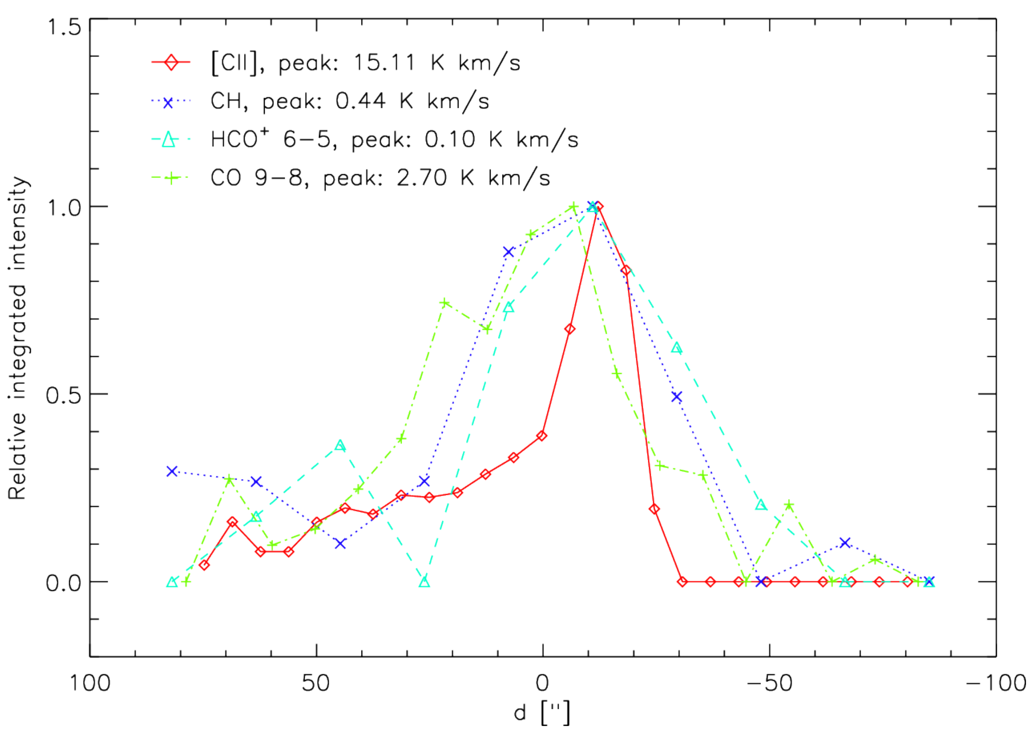
p-v diagrams reveal details of the PDR layering including the dynamical structure

Interpret line parameters

Fit of line profiles along the cut:



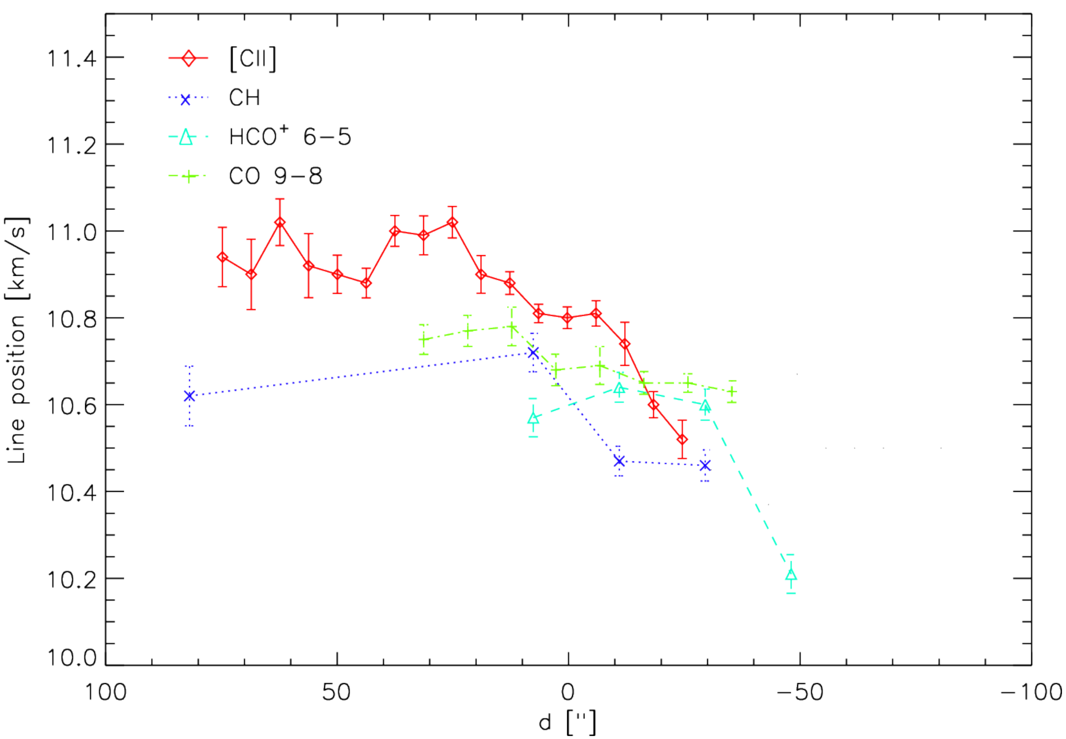
Intensity profiles:

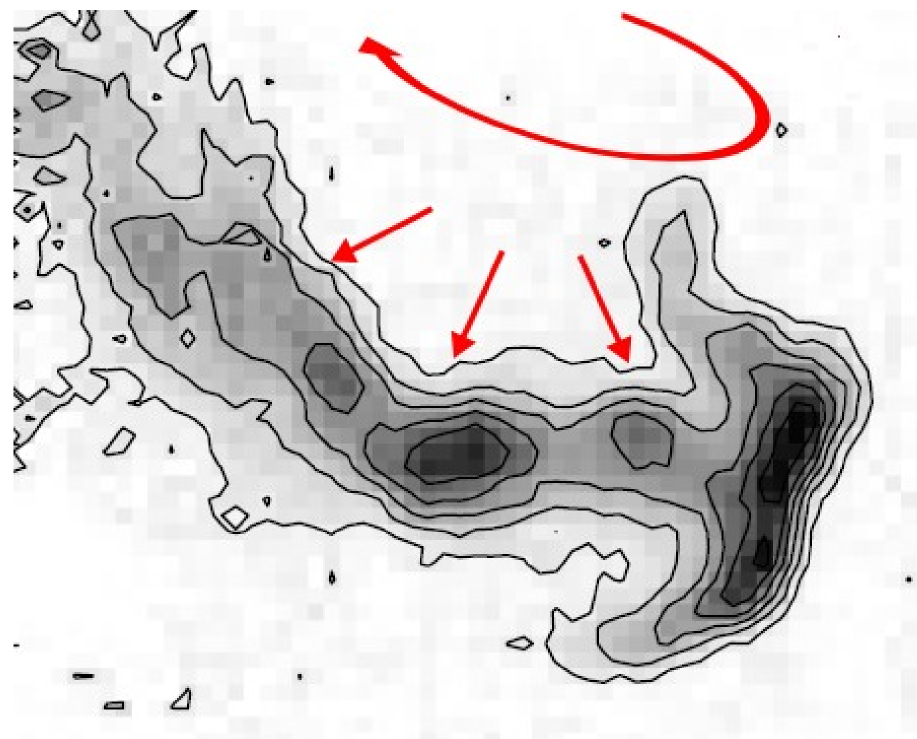


- Stratified chemical structure
- Layering $C^+ \rightarrow HCO^+ \rightarrow CO$
- C^+ in sharp surface layer
- CH extended, in between HCO^+ and CO

Interpret line parameters

Velocity structure from p-v diagrams:





Line center velocities:

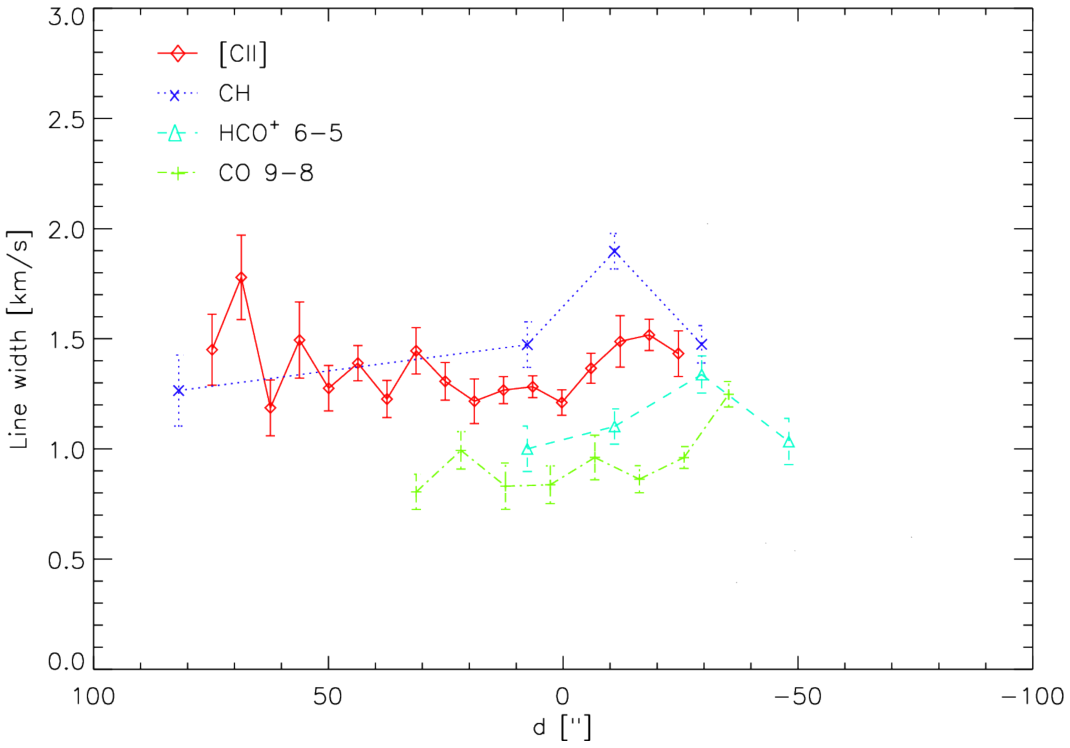
- Gradient along the neck
- Offset between [CII] and high-density tracers

Consistent with dynamical picture of Hily-Blant et al. (2005):

- Rotation of large-scale structure
- C^+ accelerated by radiation pressure

Interpret line parameters

Velocity structure from p-v diagrams:

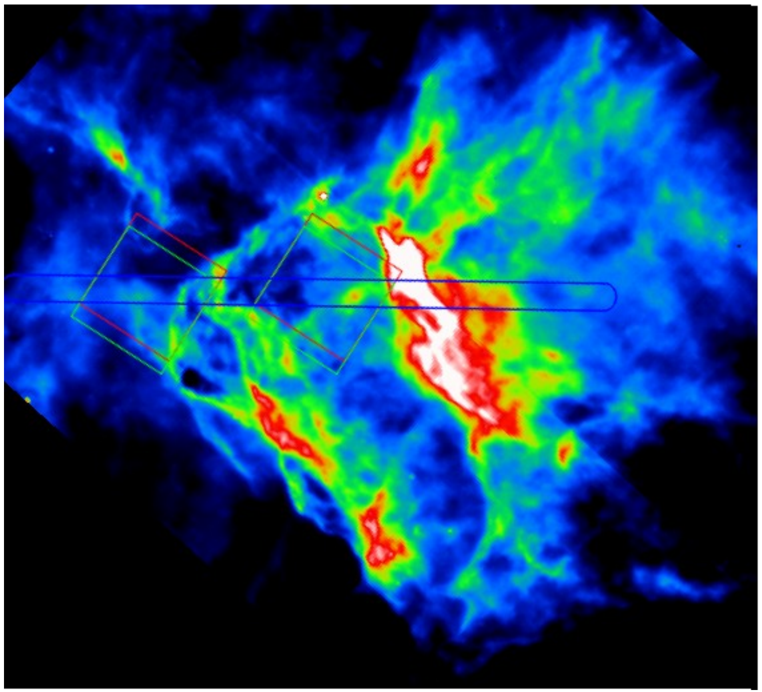


Line width:
- CH systematically broader
- Significant broadening at front

- Confirmation of expected pressure “jump” at interface
- Wider width of [CII] compared to molecules expected from stronger coupling to radiation pressure
- Wider width of CH mysterious

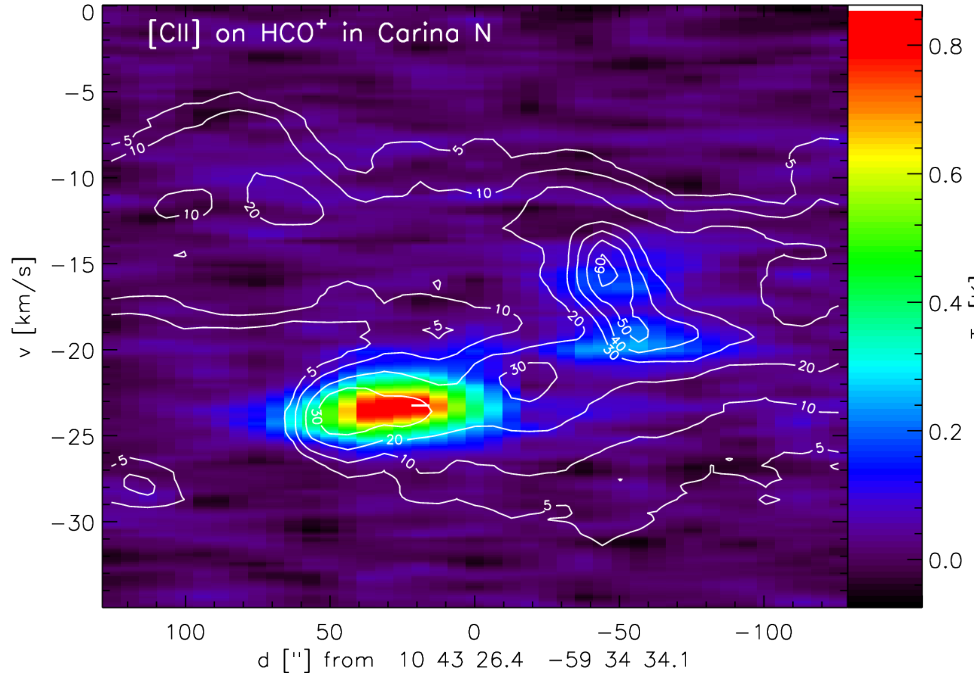
Example 2: Carina North

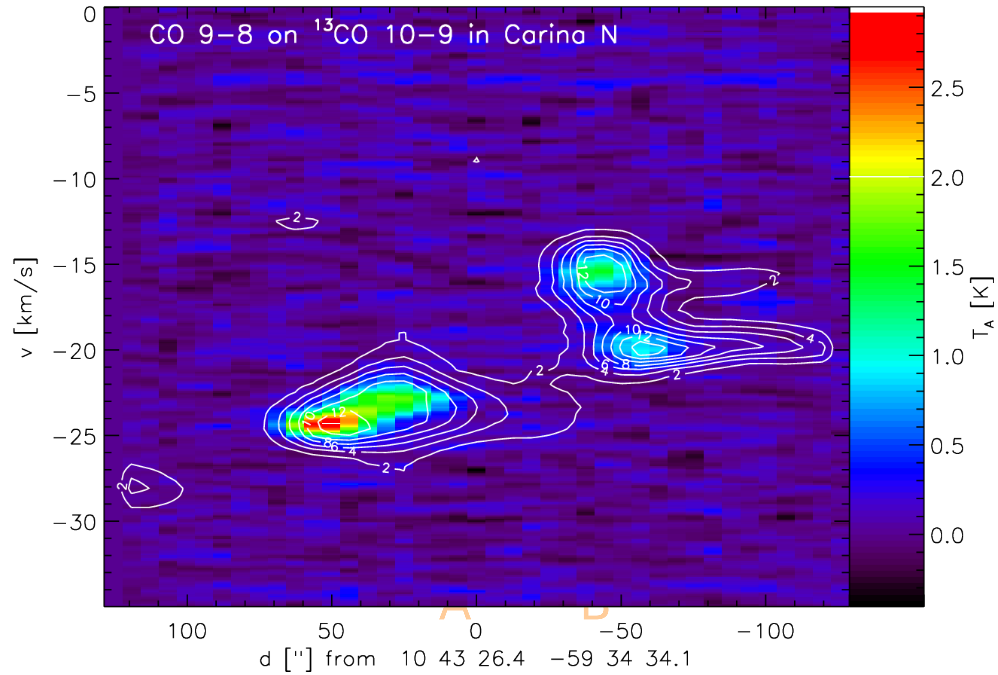
Multiple interfaces:



Cut through Carina North PDR

- Very difficult to interpret due to multiple components





Top: [CII] (contour) and HCO^+ 6-5 (color)
Bottom: CO 9-8 (contour) ^{13}CO 10-9 (color)

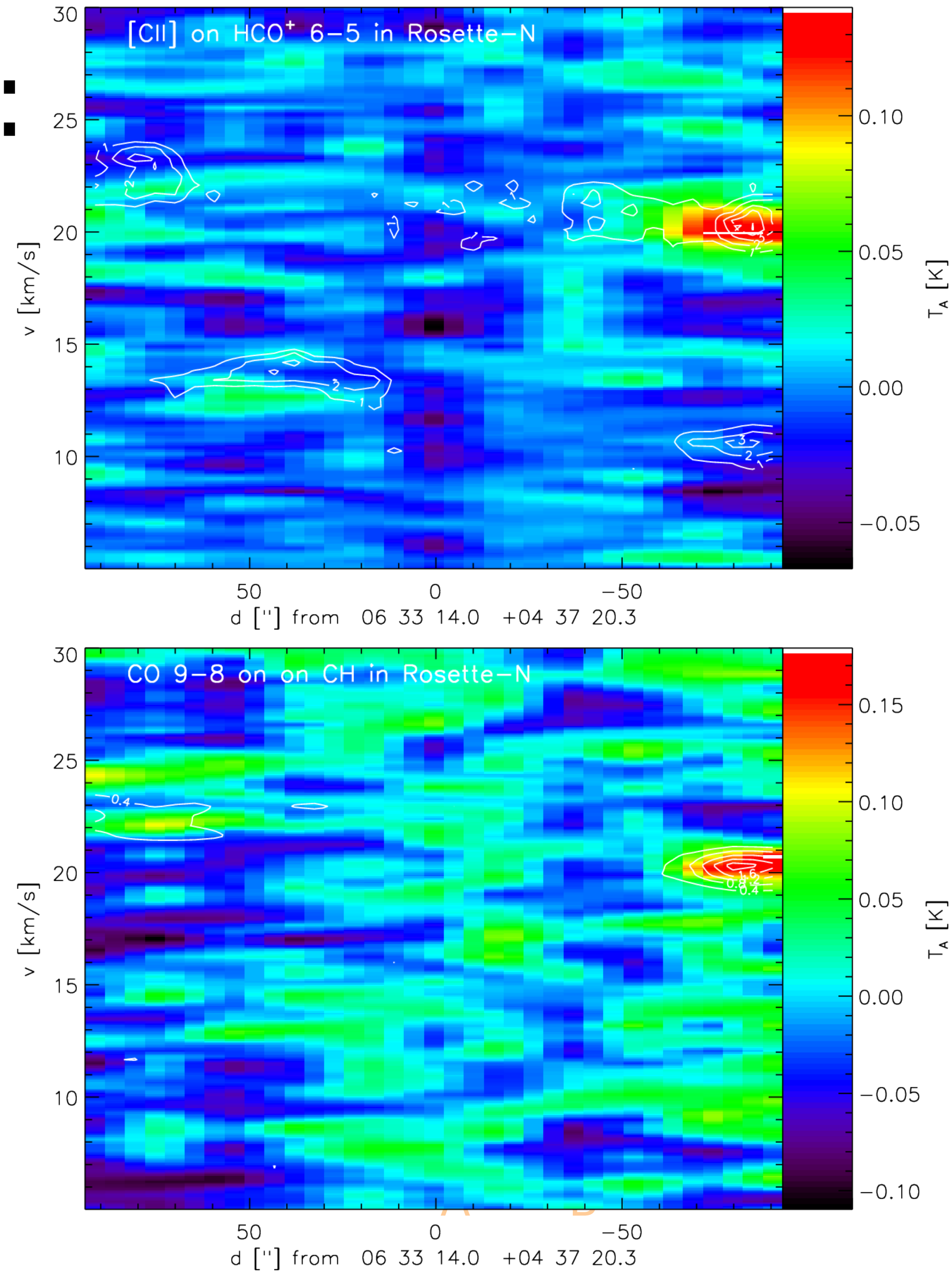
Example 3: Rosette

2 interfaces:

2 cuts through Rosette

- 2 Separate velocity components → only density clumps traced, no substructure

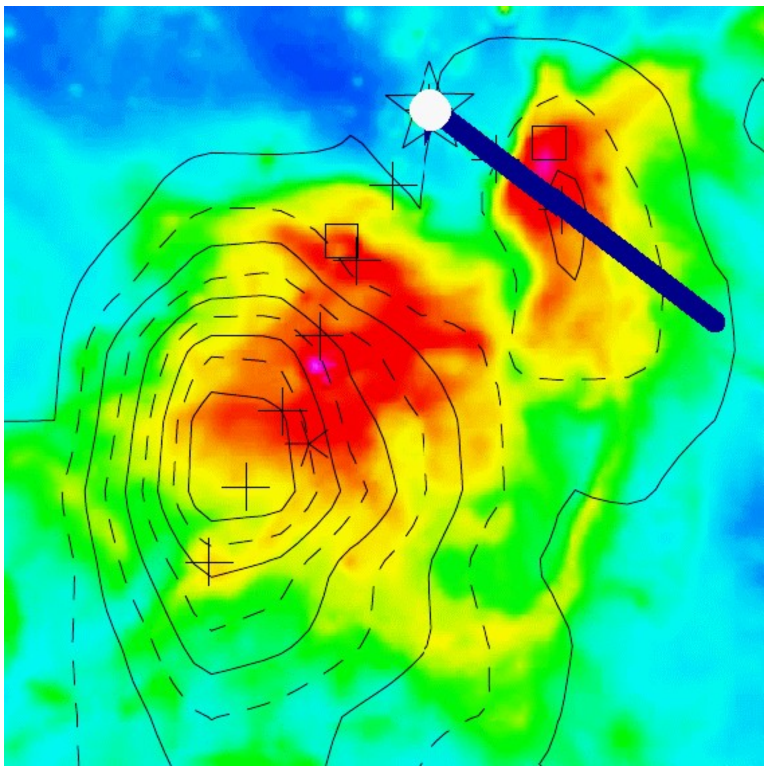
pv-examples: tilted “North” cut, UV source to the right



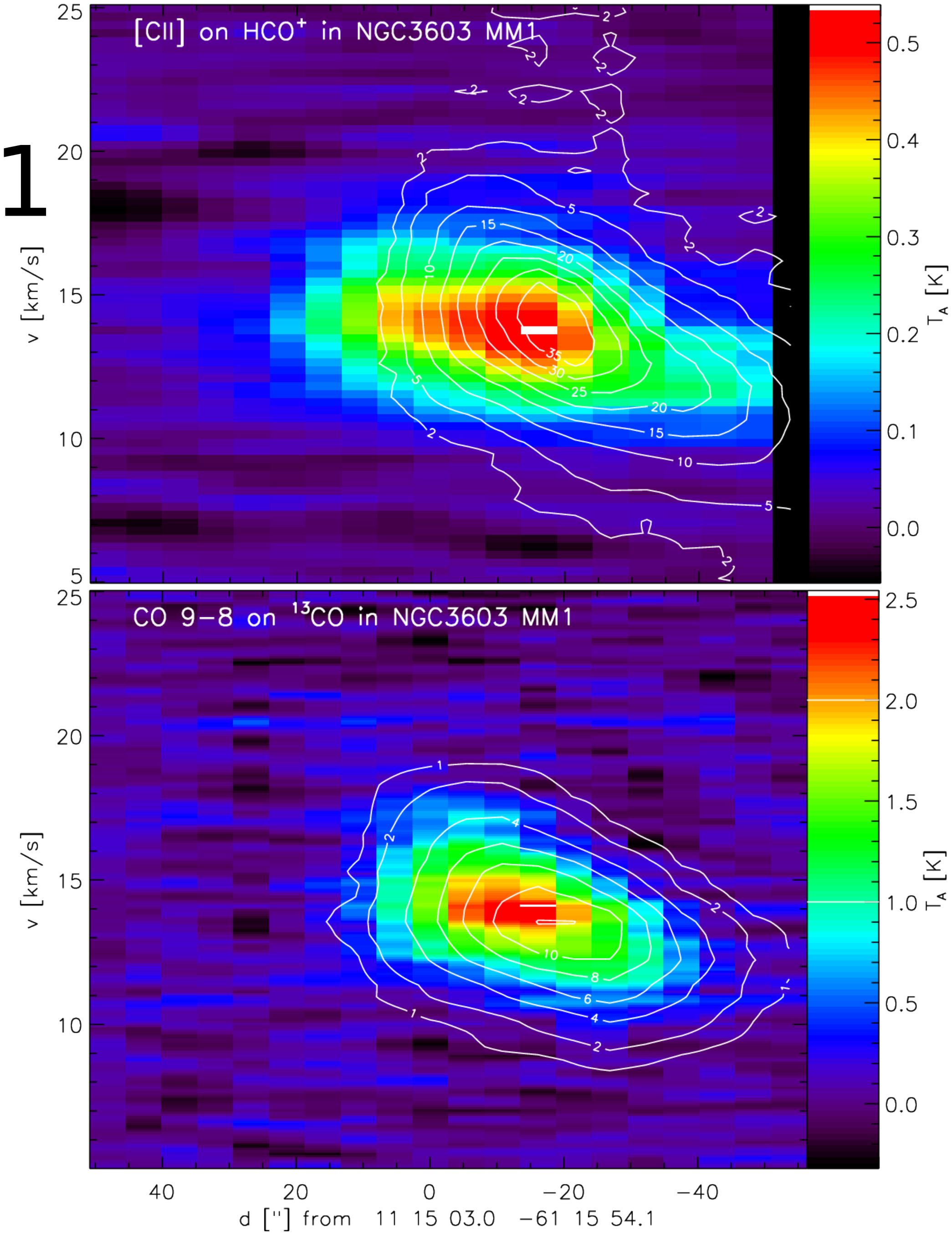
Top: [CII] (contour) and HCO^+ 6-5 (color)
Bottom: CO 9-8 (contour) on CH (color)

Example 4: NGC3603 MM1

Known velocity gradient in clump:



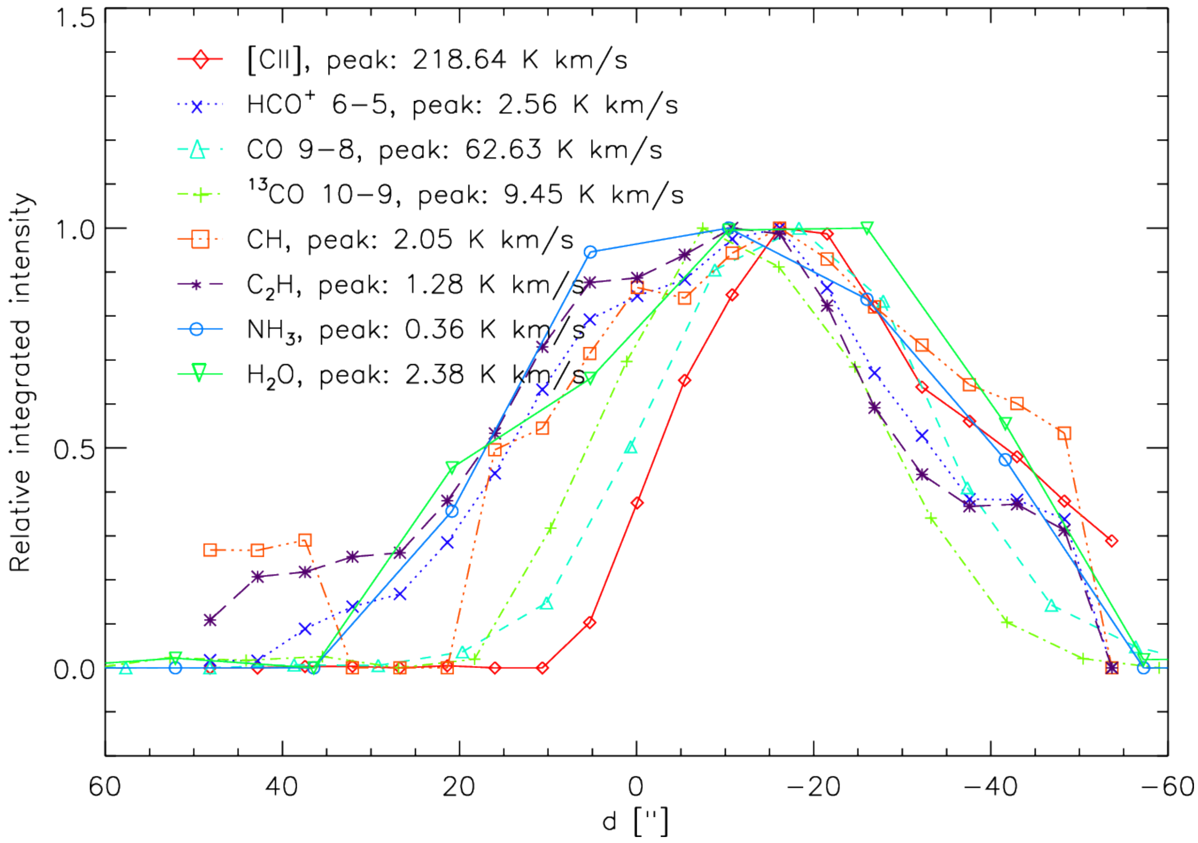
Observed cuts in NGC3603 overlaid on Spitzer 8μm



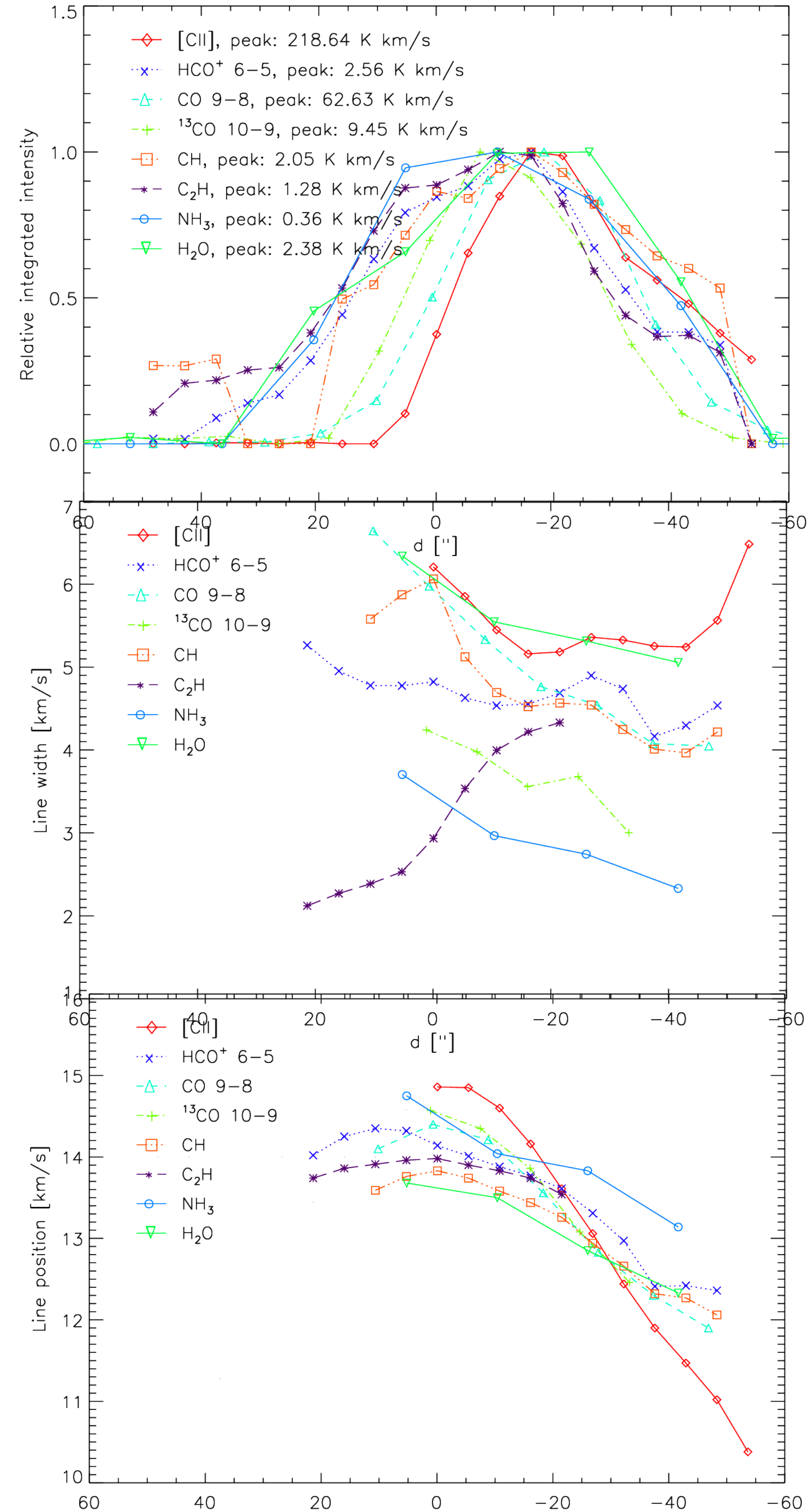
Top: [CII] (contour) and HCO^+ 6-5 (color)
Bottom: CO 9-8 (contour) ^{13}CO 10-9 (color)

NGC3603 MM1

- Chemical layering partially inverted!
  - [CII] peaks deeper in the core than all molecules
  - CO slightly deeper than ^{13}CO
- CH again very extended
- Tail of [CII] “behind” the core



NGC3603 MM1



Line position and width:

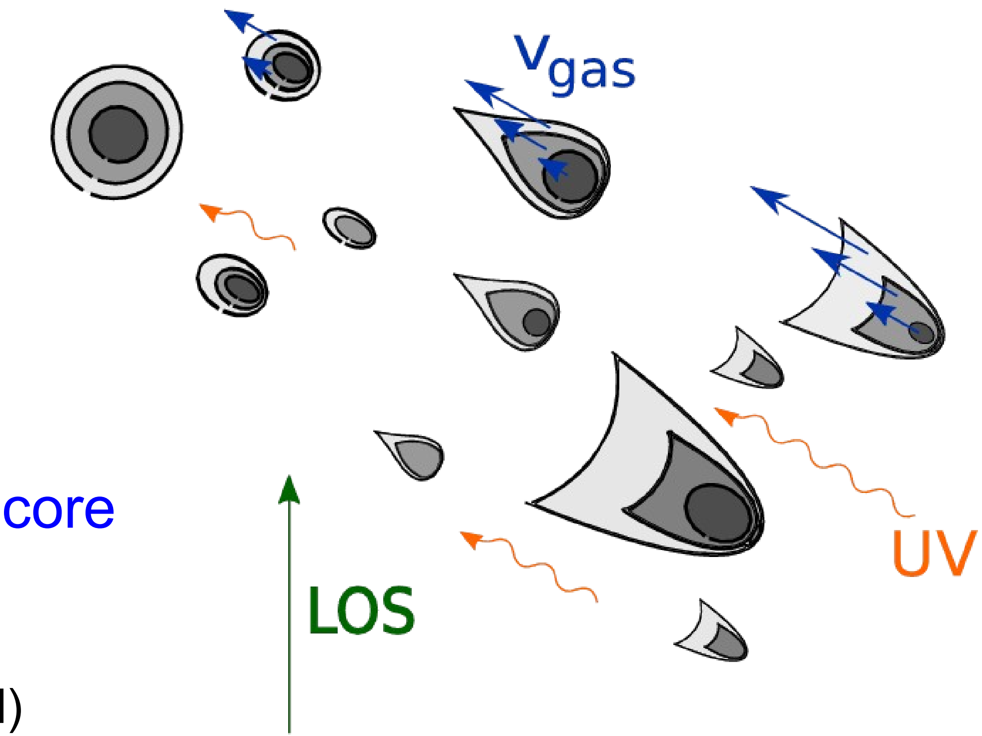
- Broadening of most lines at surface
- [CII] is red-shifted relative to molecular tracers at interface
- Stronger velocity gradient in [CII] than in molecules
- Long turbulent [CII] tail of material "behind" the core

→ C^+ must be blown from the surface into a clumpy medium

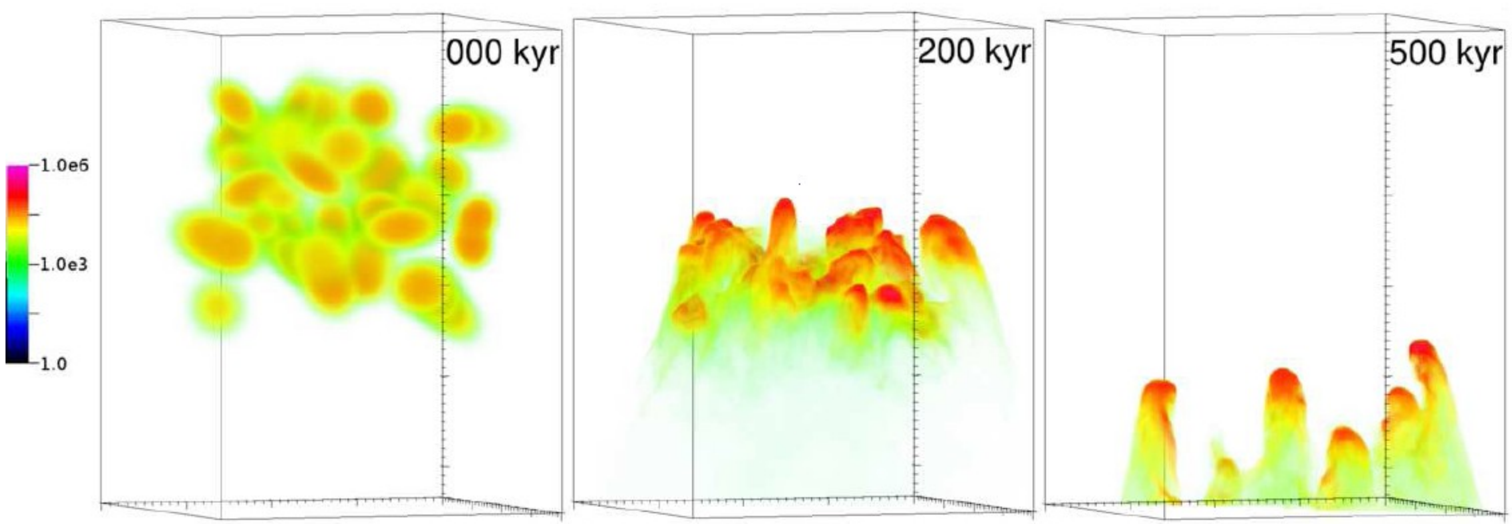
- Redshifted profiles → affected material sits behind the cluster
- The gradient along the core measures radiative (?) compression!

Interpretation

- Clumps → cometary clumps
- Evaporation flow towards cluster suppressed
- Material is “blown” into the cloud
- Compression and dispersion of the core

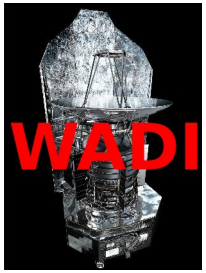


Compare: Mackey & Lim (MNRAS submitted)

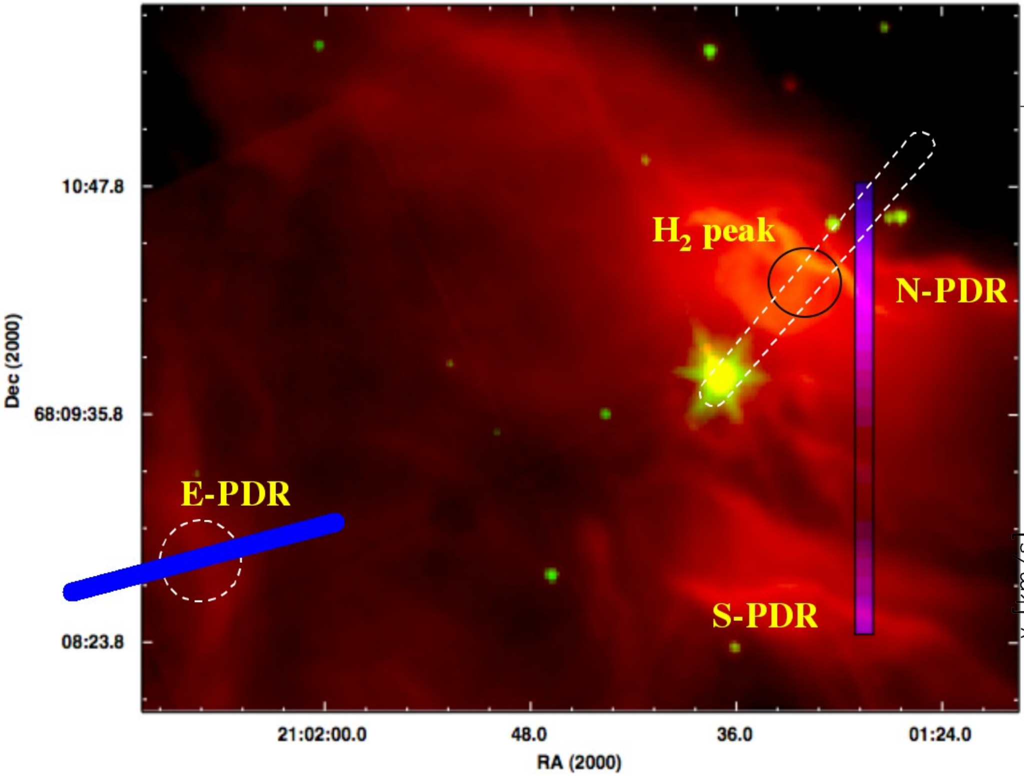


→ **Pillar formation**

Example 5: NGC 7023

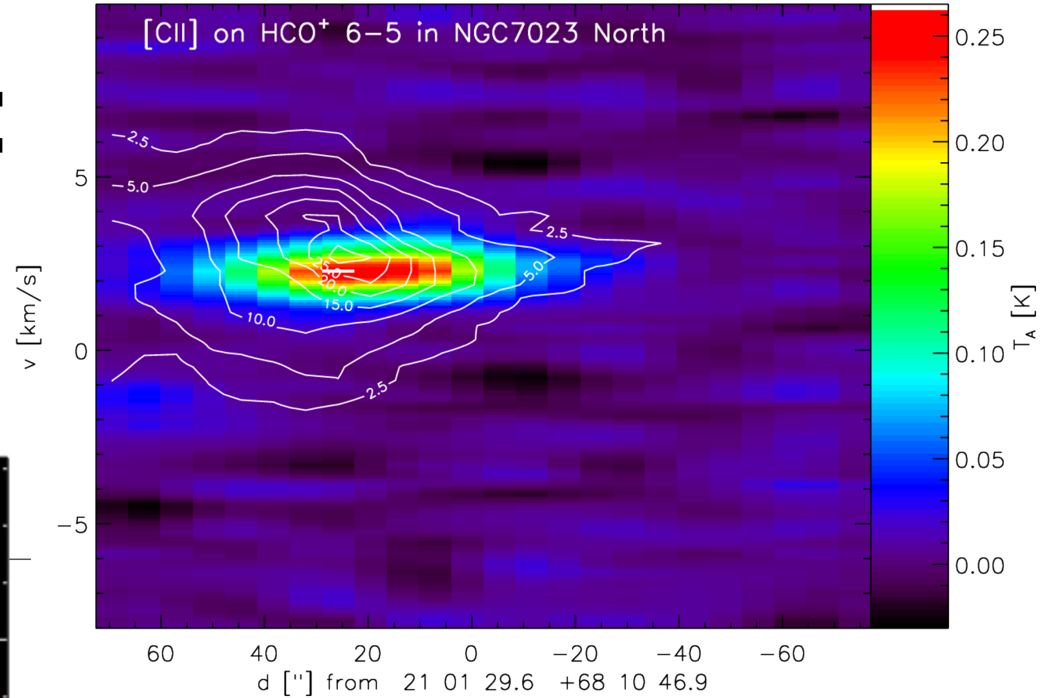


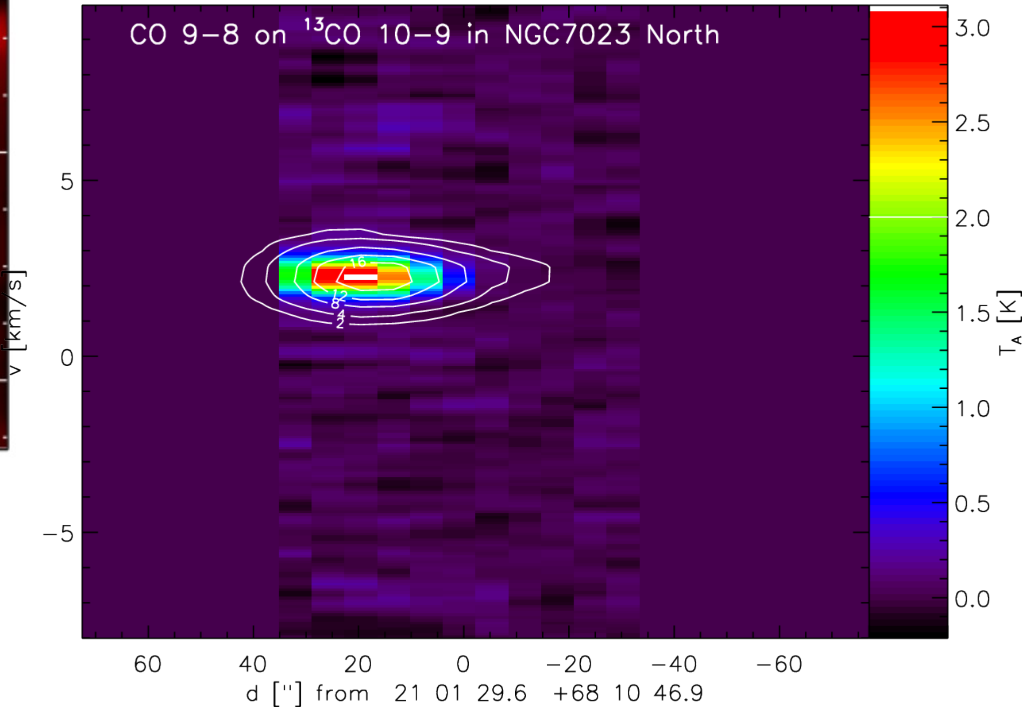
3 PDRs in one source:



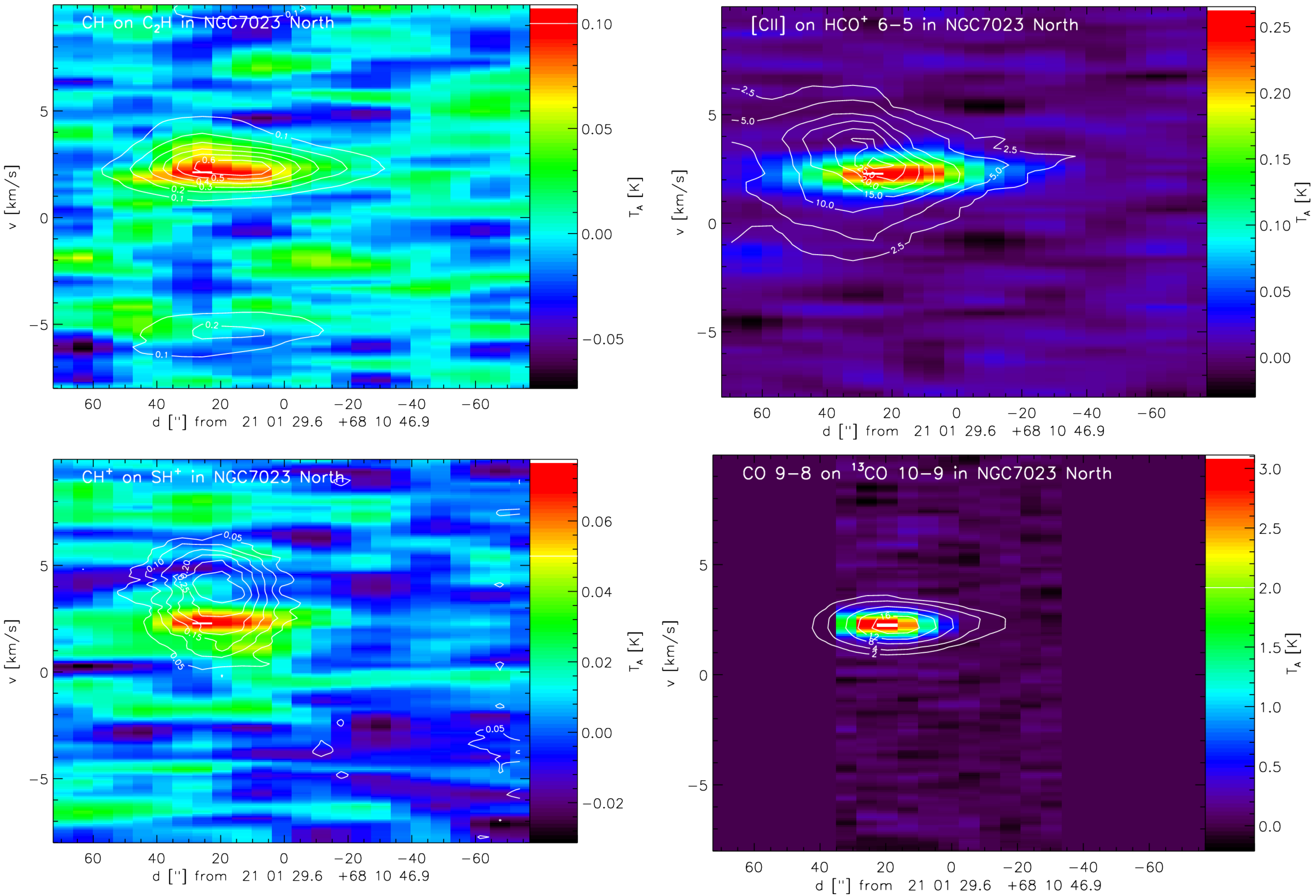
Observed cuts in NGC7023 overlaid on IRAC 3.6-8µm image

pv-examples: North cut through H_2 peak, UV source to the left





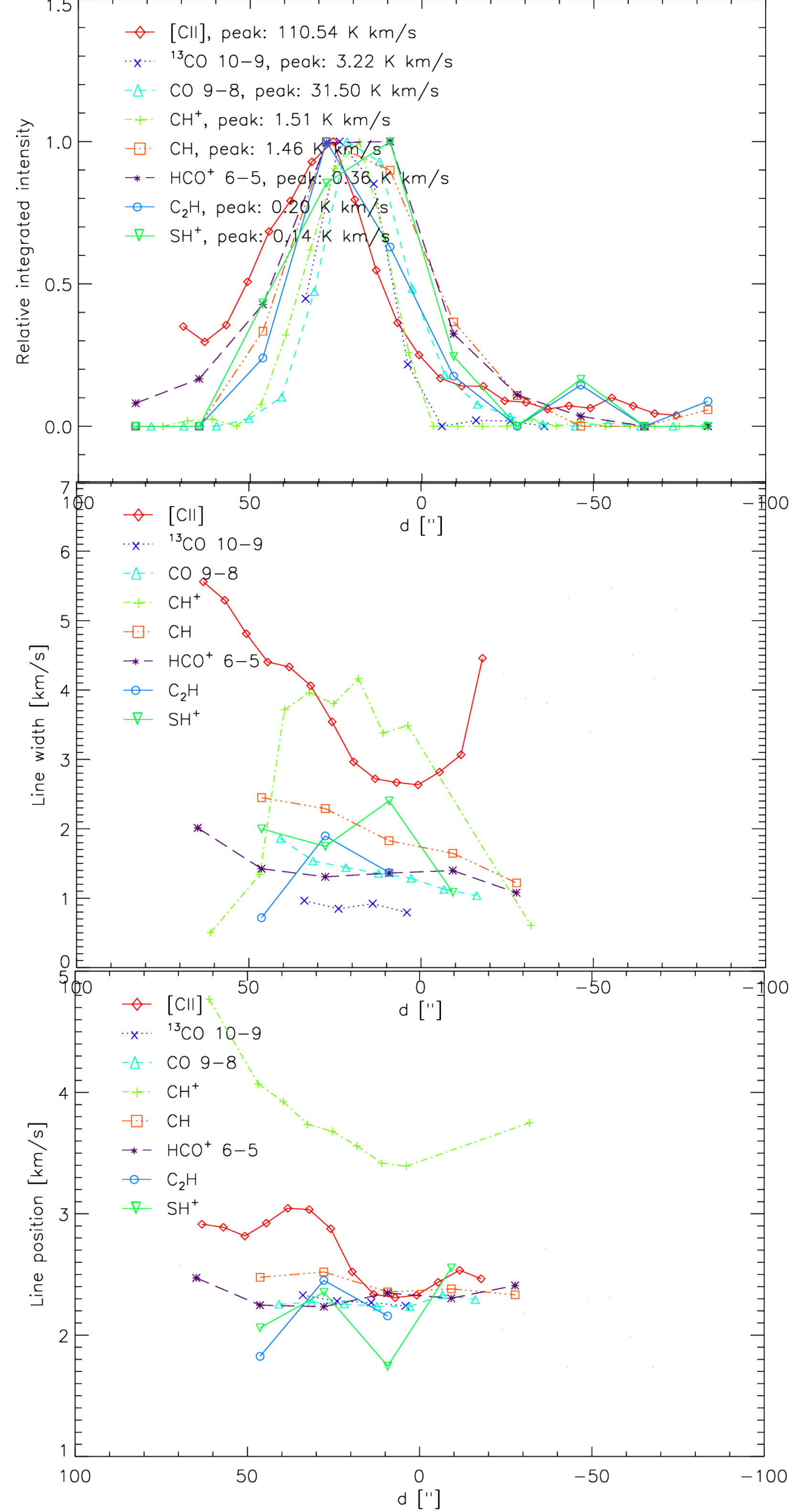
Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: ^{13}CO 10-9 (colors) + CO 9-8 (contours)



Top: C_2H (colors) + CH (contours)
Bottom: SH^+ (colors) + CH^+ (contours)

Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: ^{13}CO 10-9 (colors) + CO 9-8 (contours)

NGC 7023 N



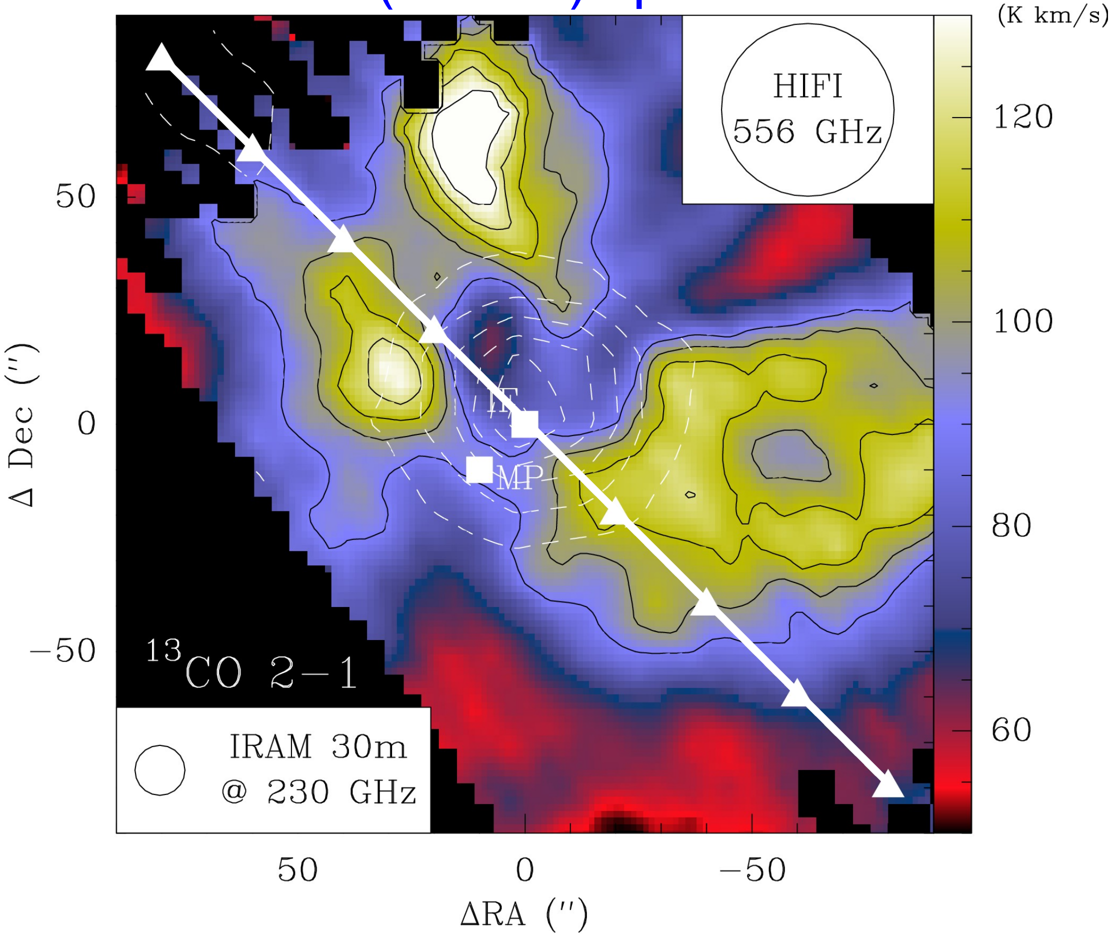
Interpret line parameters:

- “Normal” stratification structure with respect to [CII] – molecules
- No significant positional shift between other tracers
- Most lines broadened at interface, [CII] most significantly
- Smooth transition of [CII] into HII region
- CH^{+} significantly broader than other molecular lines (except [CII])
  - CH^{+} velocity structure overall different

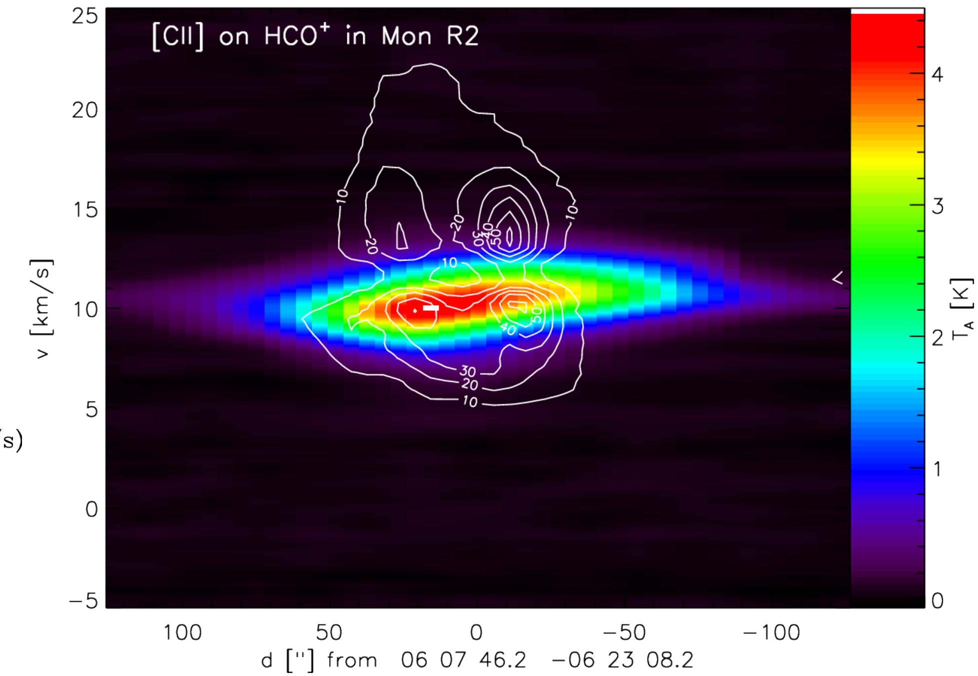
  → origin (?)

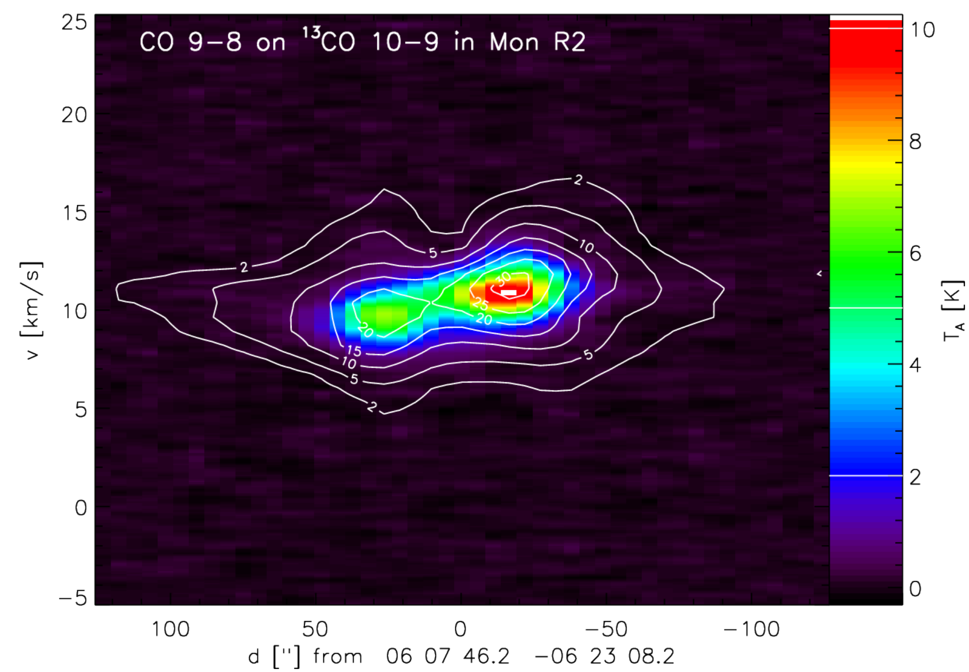
Example 6: Mon R2

UCHII with (almost) spherical PDR:

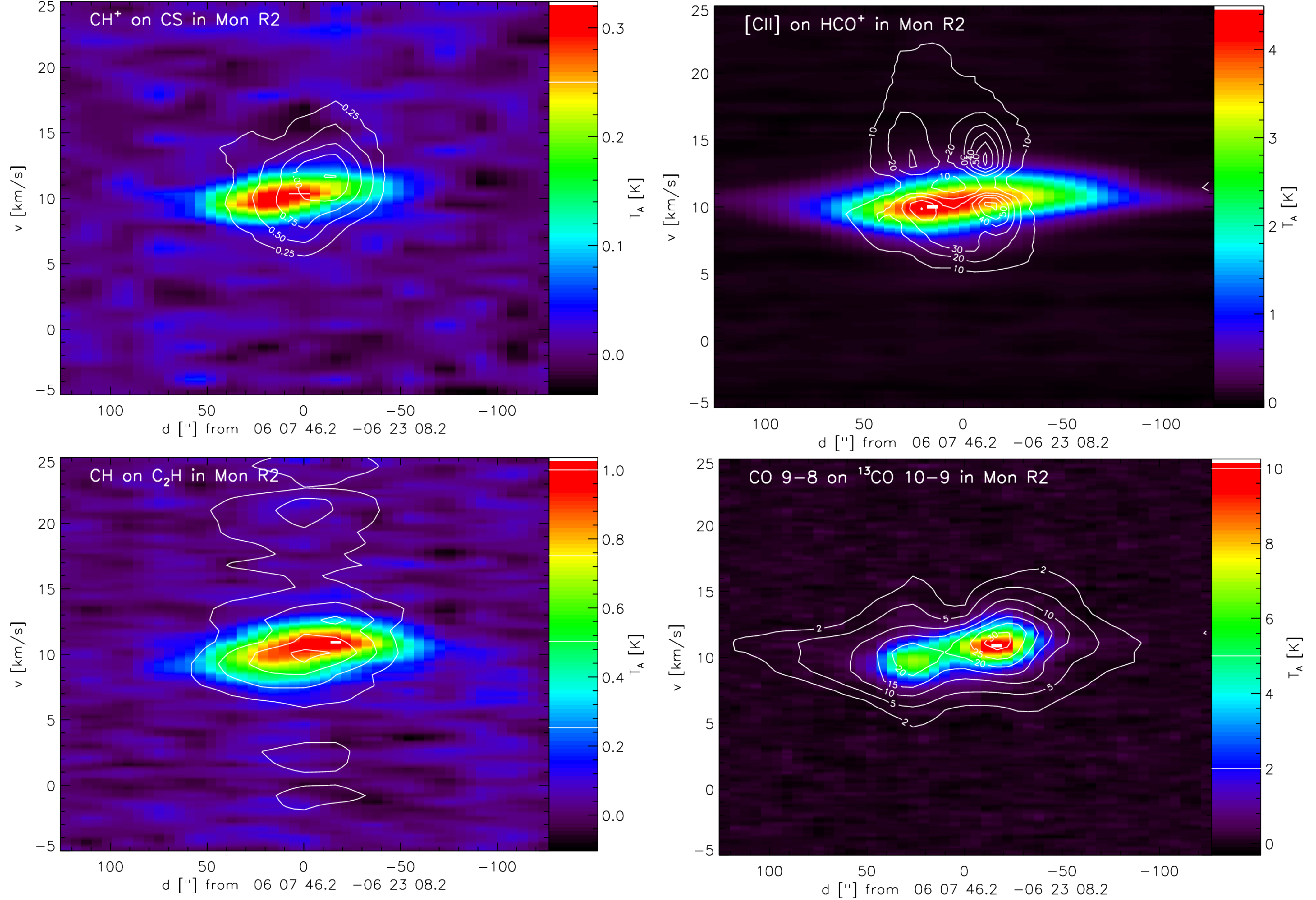


Observed cuts in Mon R2 overlaid on ^{13}CO 2-1 and H recombination lines (dashes) showing the HII region



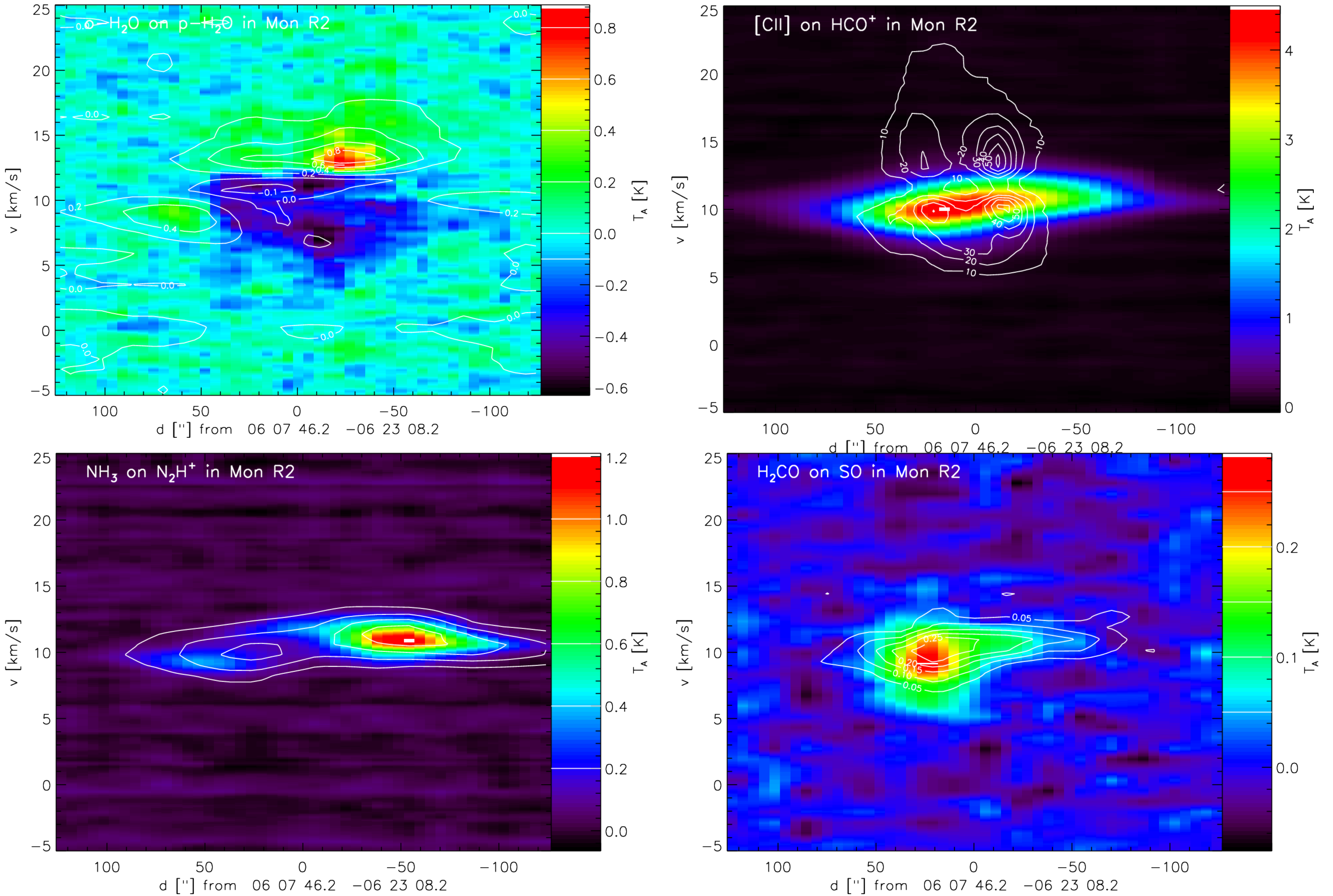


Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: ^{13}CO 10-9 (colors) + CO 9-8 (contours)



Top: CS 10-9 (colors) + CH^+ (contours).
Bottom: C_2H (colors) + CH (contours)

Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: ^{13}CO 10-9 (colors) + CO 9-8 (contours)



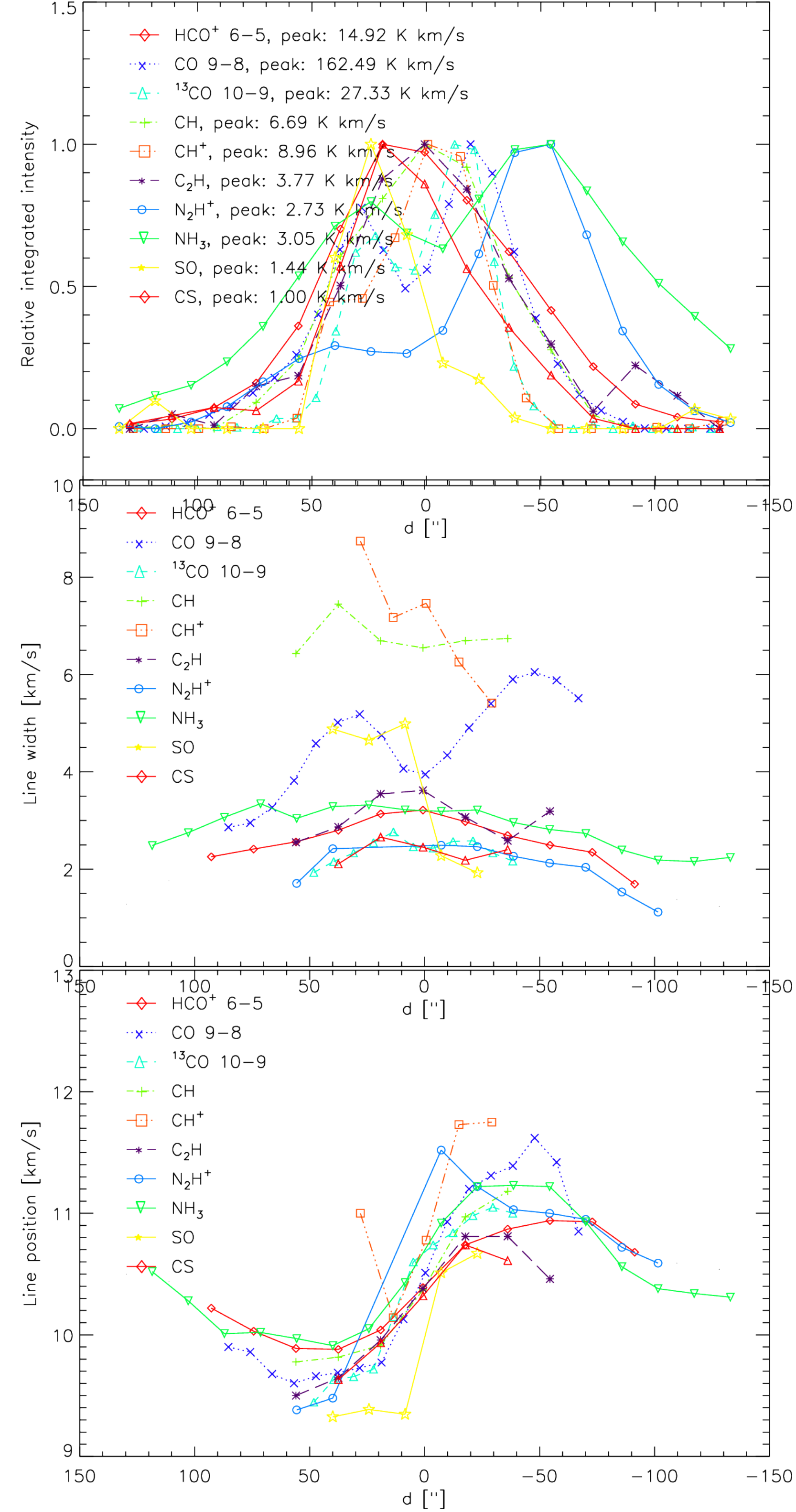
Top: p-H_2O (colors) + o-H_2O (contours).
Bottom: N_2H^+ (colors) + NH_3 (contours)

Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: SO (colors) + H_2CO (contours)

Mon R2

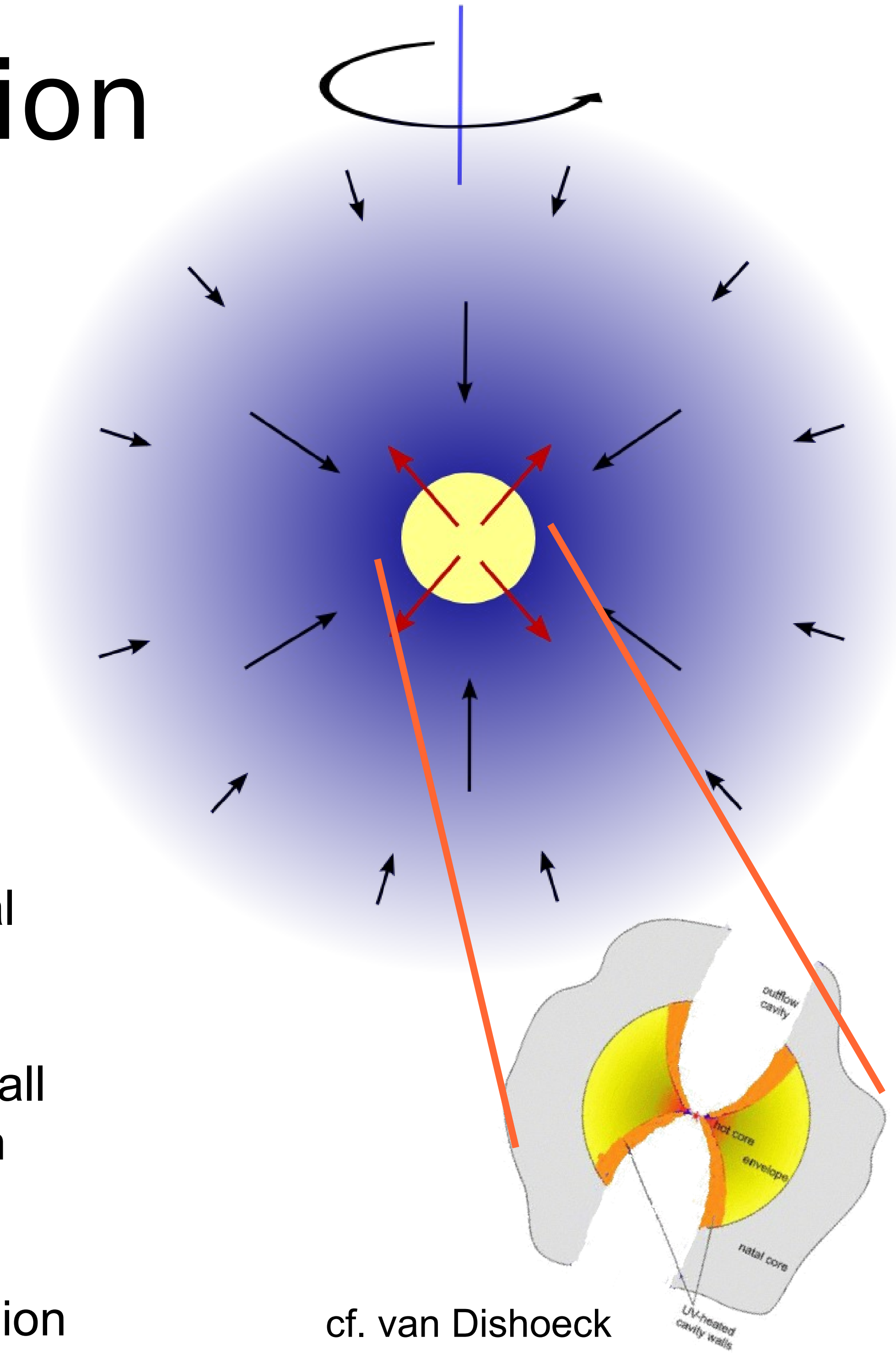
Interpret line parameters:

- No reasonable parametrization of double-peaked [CII] lines and water lines with absorption
- CH^+ also shows a well separated absorption component
    - Forground ?
    - Separate expansion layer ?
- CH^+ again very broad from source
- 2 clumps/PDR interfaces not equally prominent in different tracers
- Different velocity distribution from hot and cold tracers
- S-shape tracing large-scale rotation



Interpretation

- Large-scale infalling cloud
  - Increasing density
  - Accelerated infall
  - Large-scale rotation
- Expanding walls of HII region
  - Harbors bipolar outflow



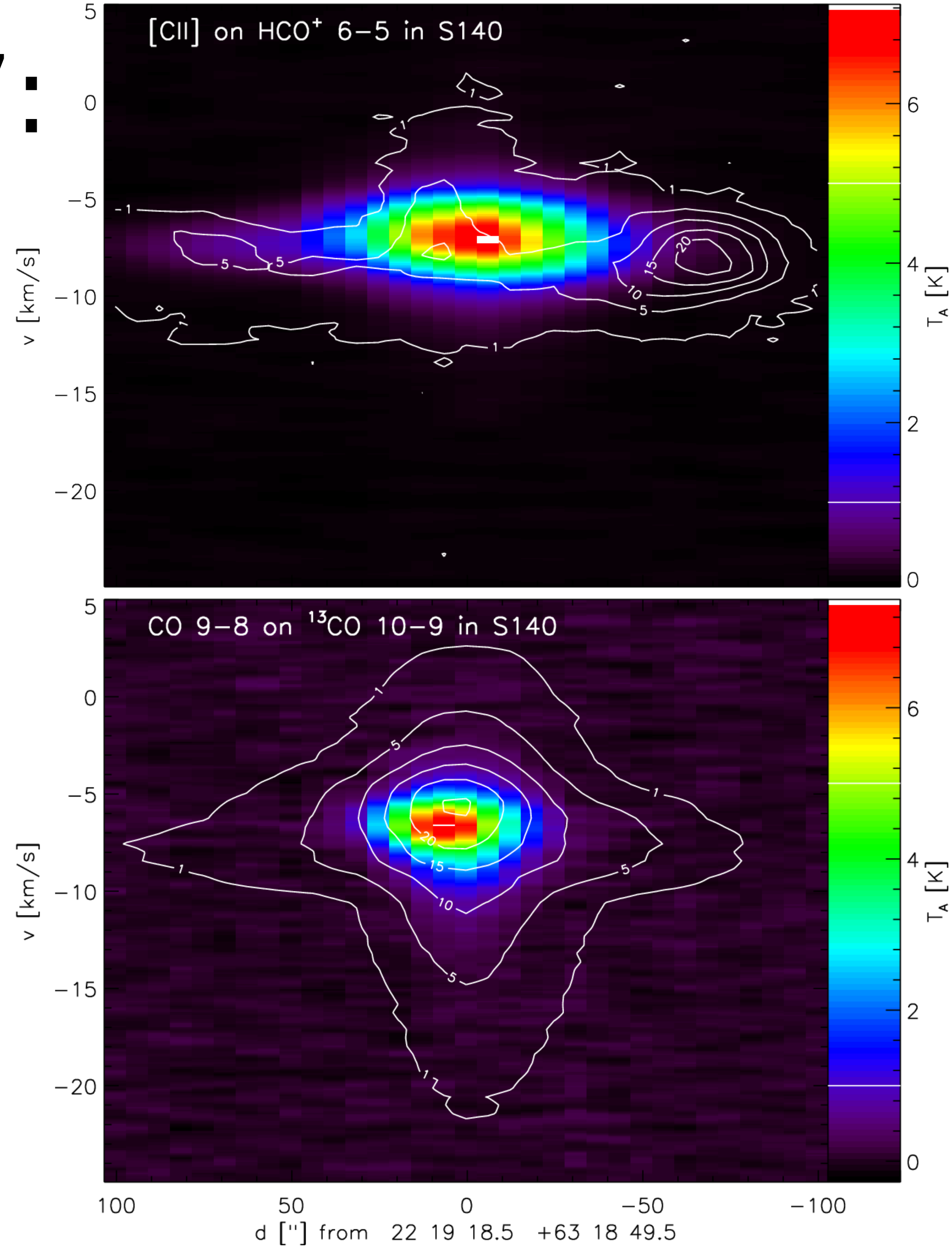
cf. van Dishoeck

- CO 9-8 shows the PDR
  - Illumiated dense molecular material
- Water in absorption for low velocities, red-shifted velocities in emission
  - Emission from backside or core-infall
- Double-peaked [CII] profile mainly from walls of HII region
  - Wings trace ionized flow
  - Some self-absorption in the HII region

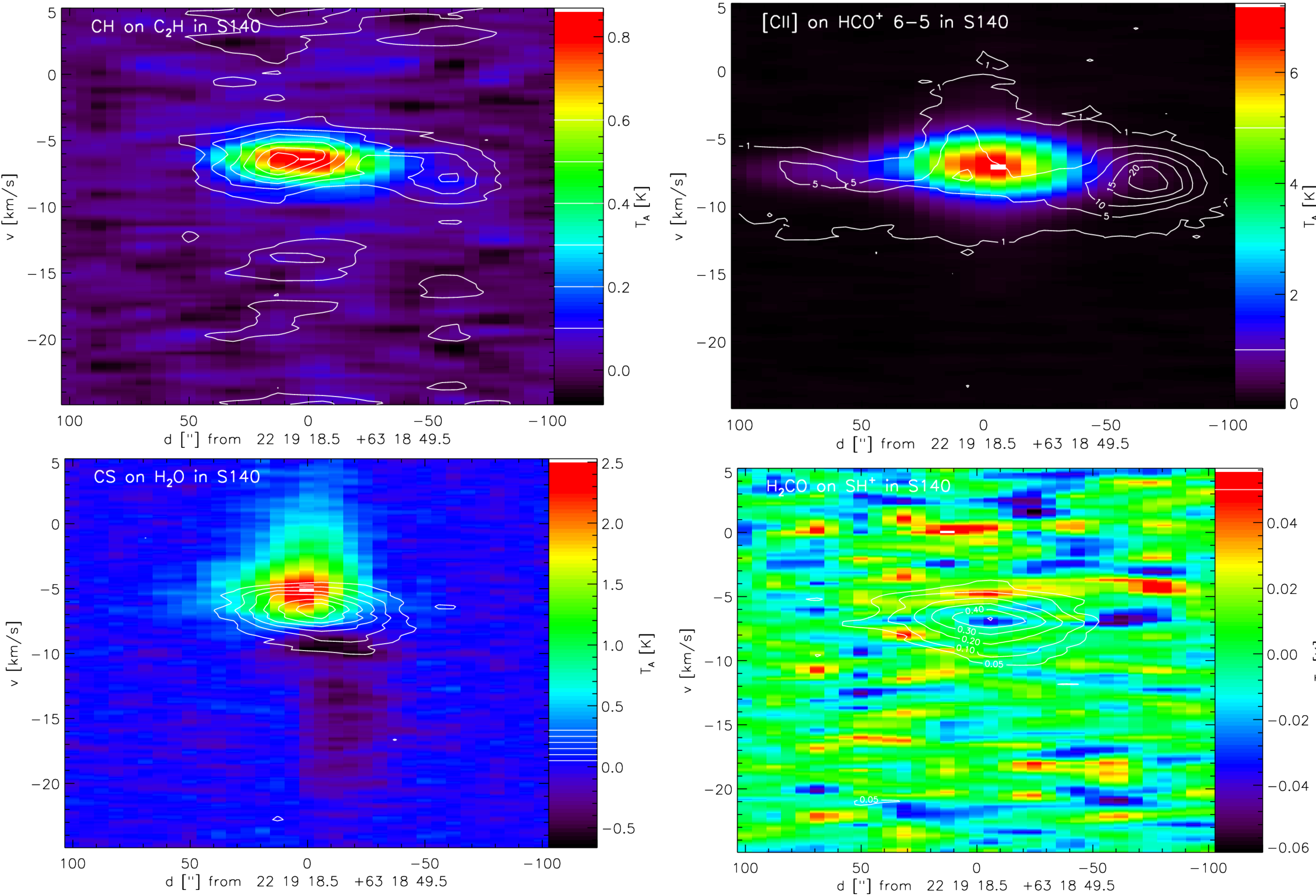
Example 7: S140

External PDR + embedded source IRS1 with internal PDRs:

Observed cuts in S140 overlaid on IRAC 3.6-8µm image



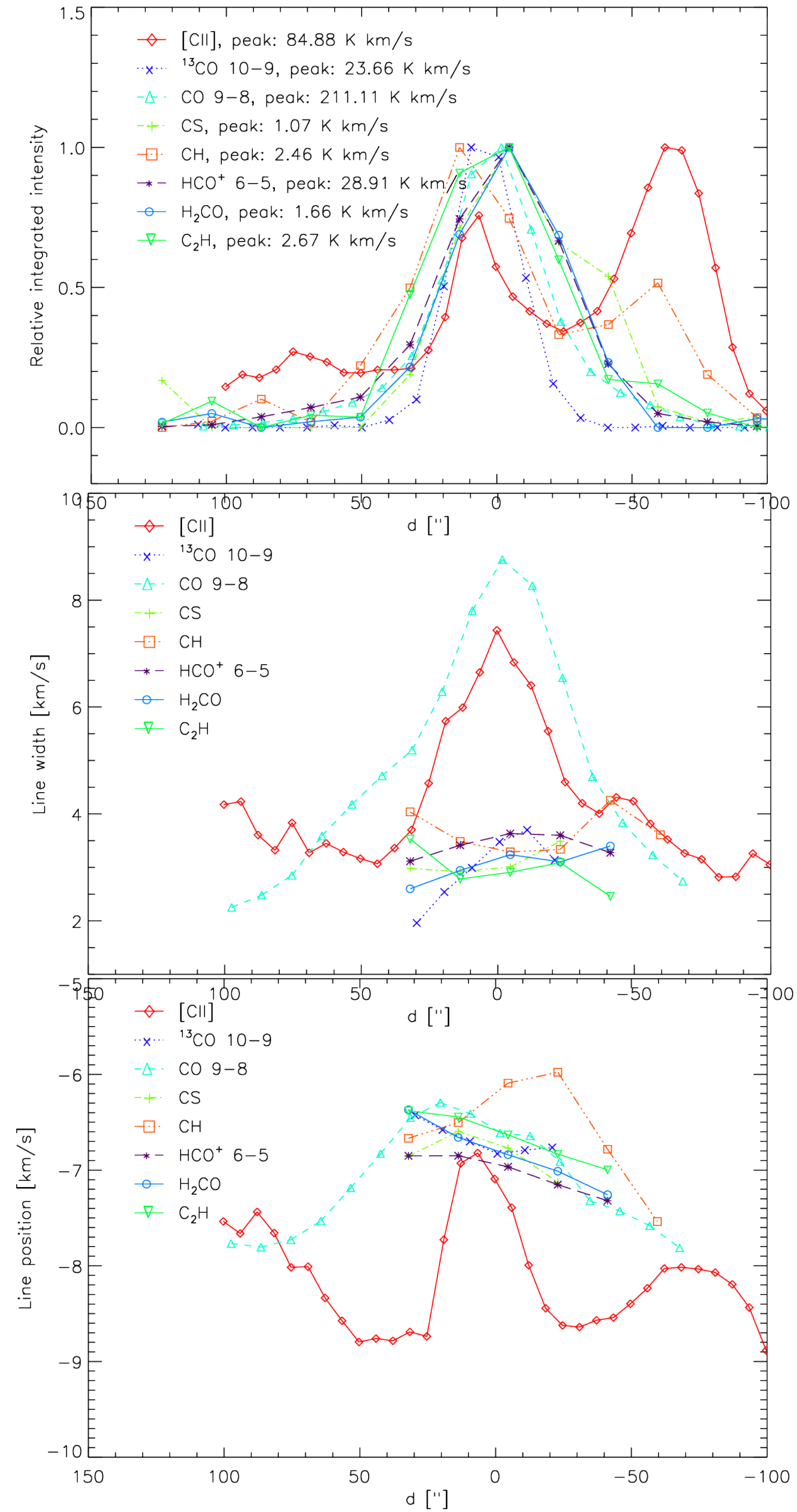
Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: ^{13}CO 10-9 (colors) + CO 9-8 (contours)



Top: C_2H (colors) + CH (contours)
Bottom: SH^+ (colors) + CH^+ (contours)

Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: ^{13}CO 10-9 (colors) + CO 9-8 (contours)

S140



Interpret line parameters:

- Very different outflow characteristics from IRS1 seen in [CII] and $CO+H_2O$
  - Red outflow in [CII]
  - Blue outflow in CO and H_2O absorption
- PDR at interface only showing up in [CII] and CH
  - [CII] much brighter than at IRS1
- IRS1 is very similar to Mon R2 in all molecular tracers, but very different in [CII]
  - Geometry of inner ionized region unclear

Summary

- Radiation pressure driven PDR dynamics is complex
  - Pressure jump at the surface confirmed
  - Chemical stratification in PDRs often resolved
    - But inversion possible due to stronger coupling of interclump gas tracers to radiative pressure
    - Line width sequence: [CII]/CH^+ - CH – other molecules
  - Significant dispersion of gas traced
  - Possibly first direct observation of radiative core compression
  - No evaporation flows!
  - No indication of turbulent stirring through radiation