The dynamics of PDRs from Herschel observations

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Motivation:
What happens here?

How does radiation from young stars affect their environment?

→ WADI science topics:

- chemistry,
- energy balance,
- dynamics.

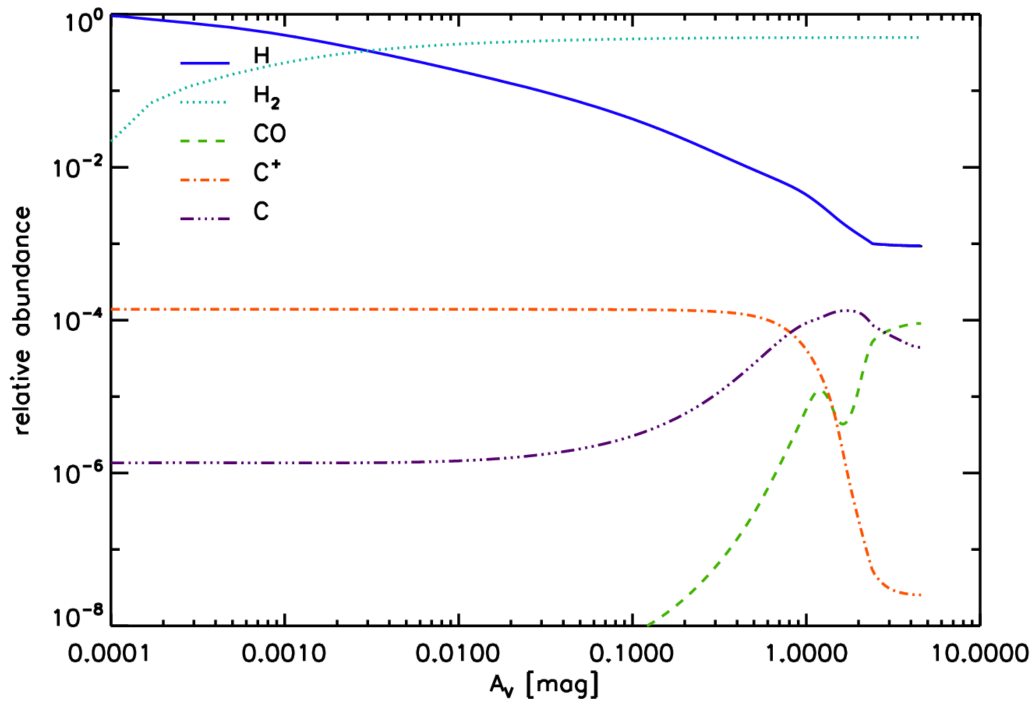
Pillars in Rosette (HOBYS team: Motte et al. 2010)

Does it **trigger** or **prevent** further star formation?

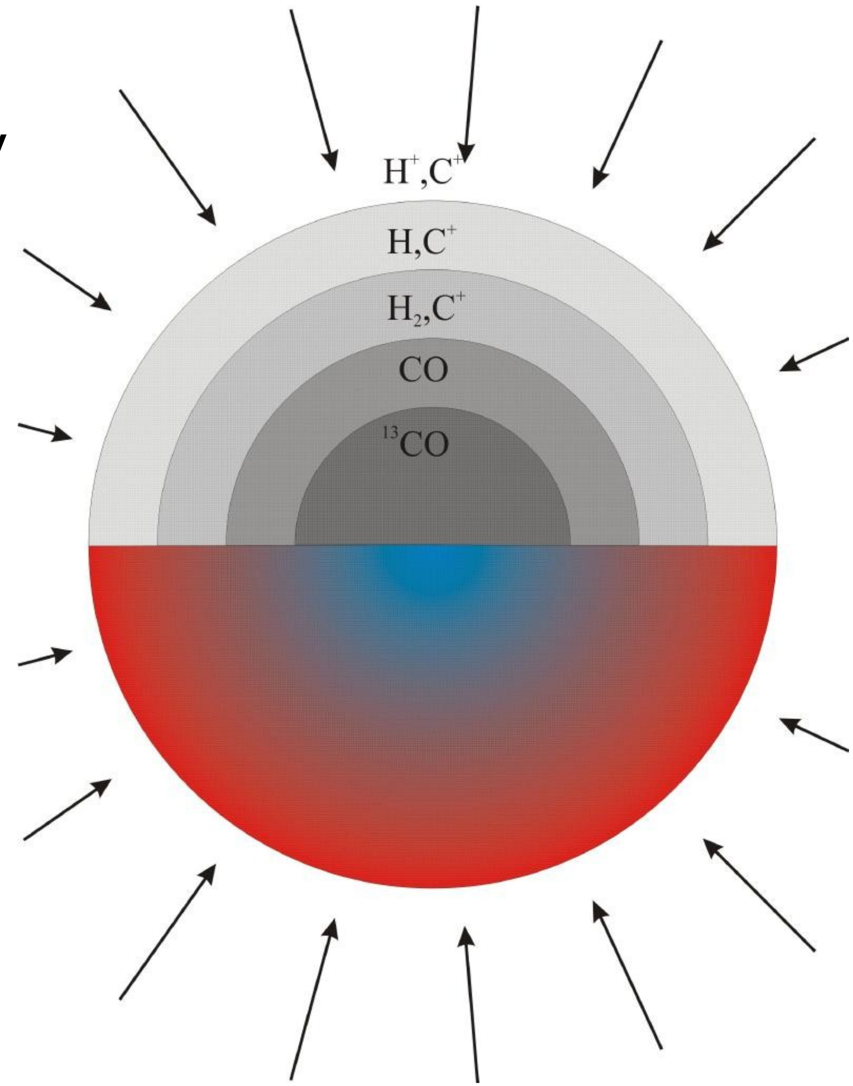
What do we expect?

Chemical structure:

- Layering of species as a function of UV field



Abundance of selected species as a function of optical depth from the cloud surface (KOSMA-τ model with $\chi = 1$, $M_{tot} = 100M_{\odot}$, $n = 500cm^{-3}$)



see talk by M. Röllig

What do we expect?

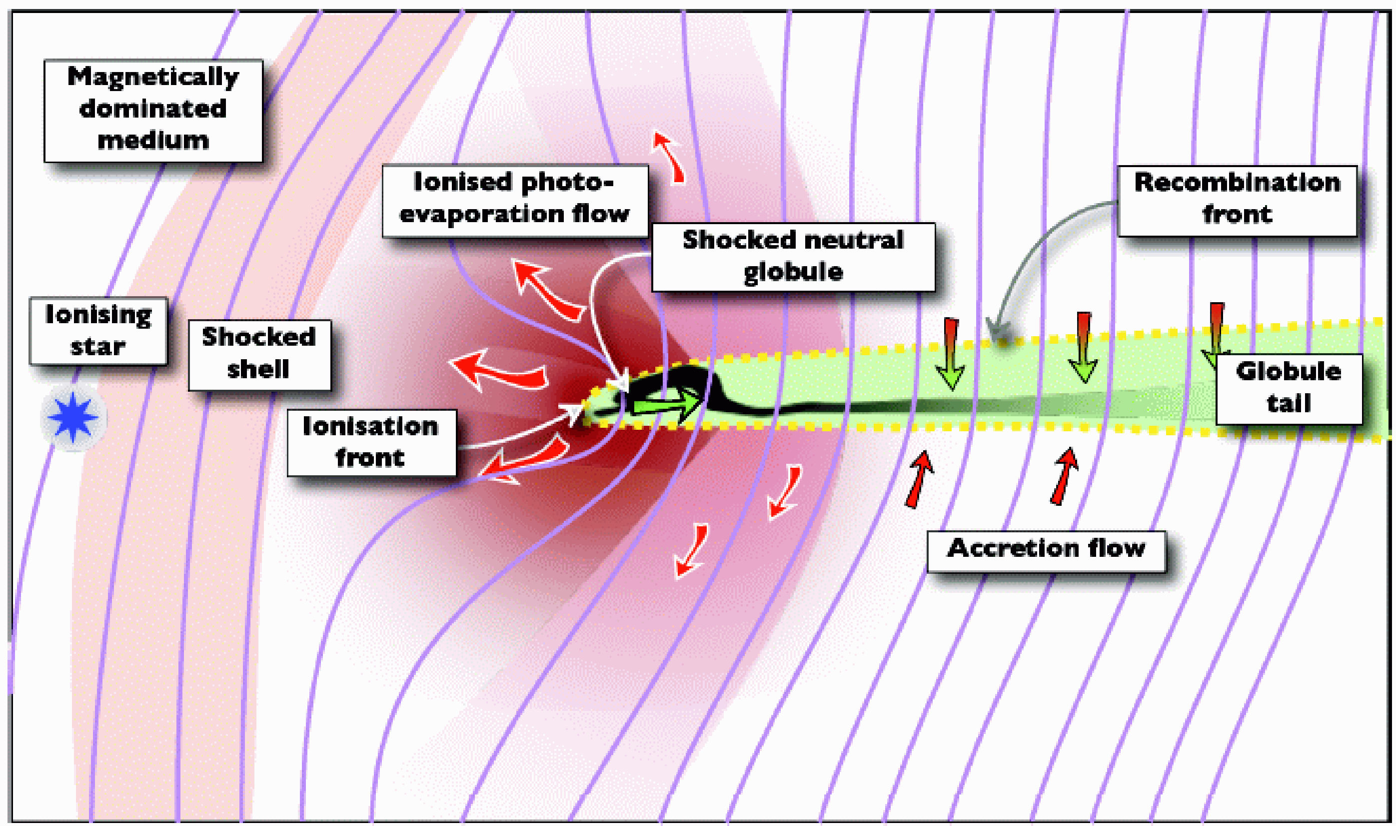
Dynamics and kinematics:

- 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



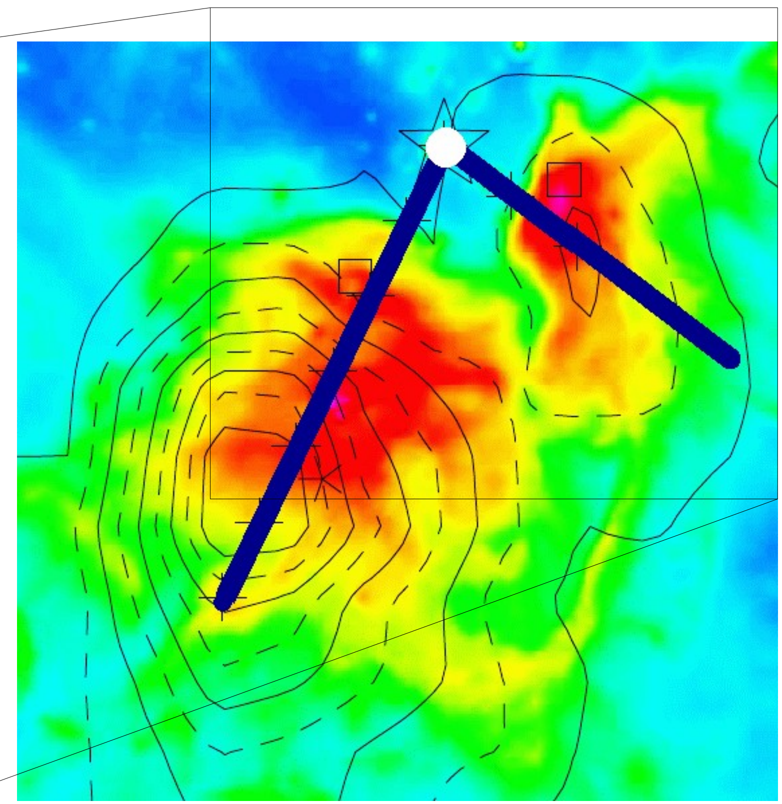
3-D MHD model by Henney et al. (2009)

HIFI Observations

Measure layering structure - example: NGC3603

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

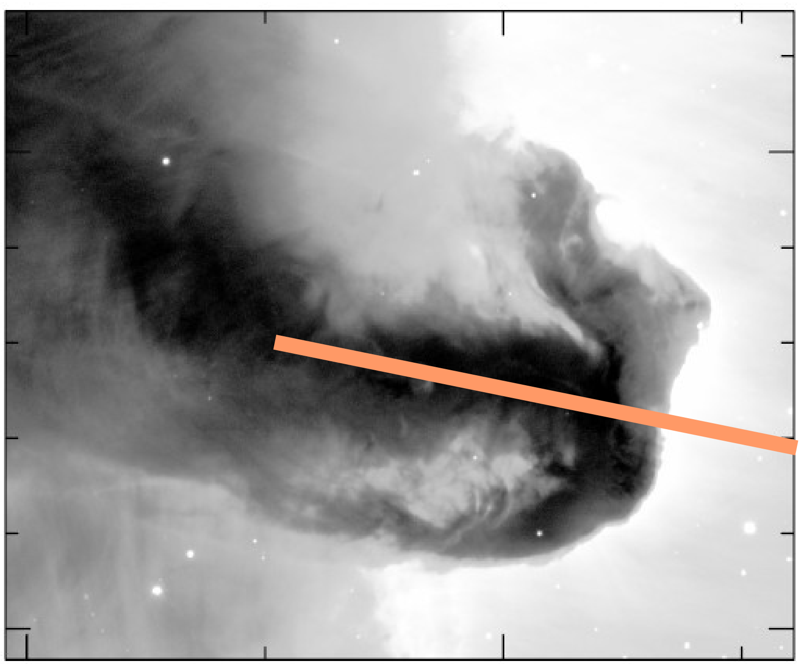
Pillars at PDR fronts (HST, Brandner et al. 2000)

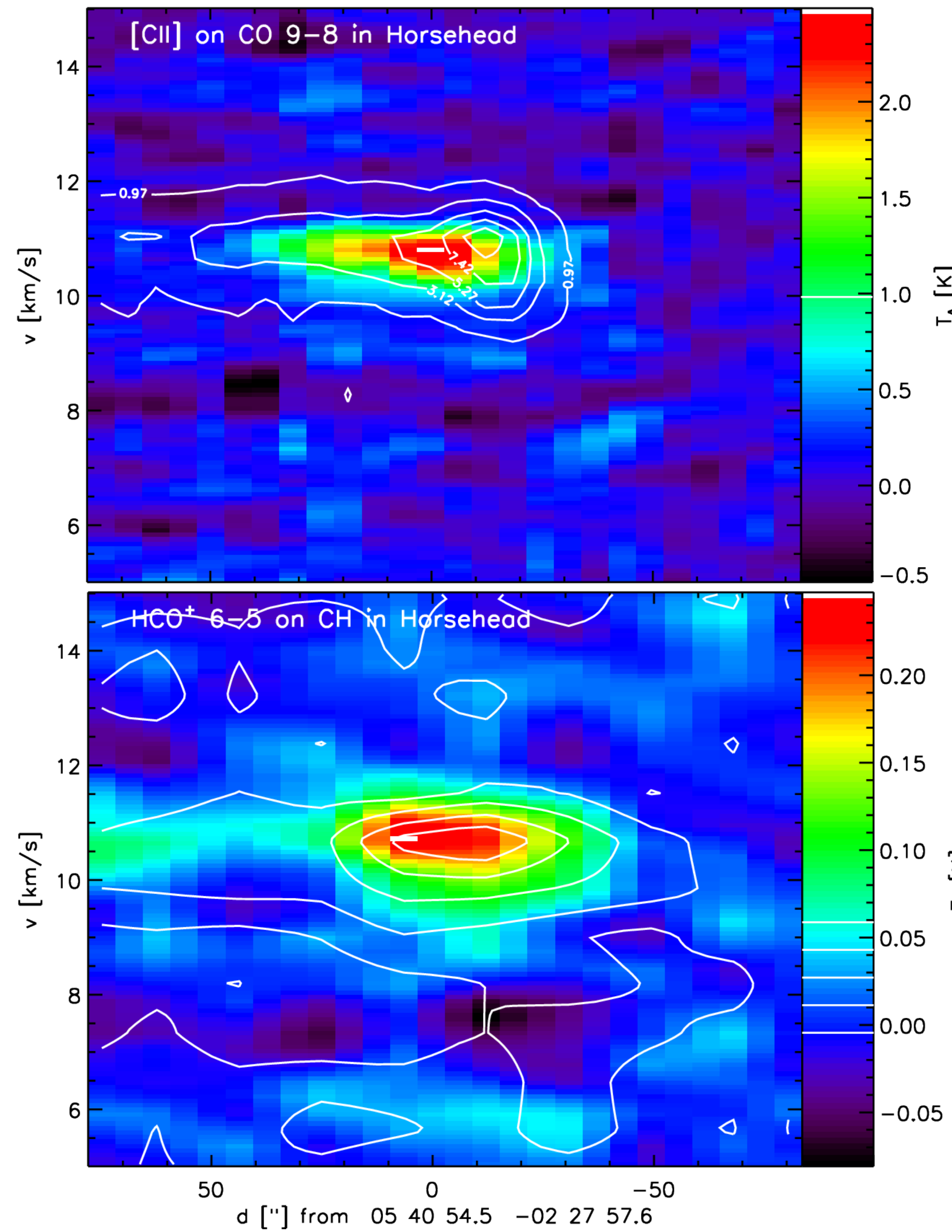


Observed cuts overlaid on Spitzer 8μm (color) and CO 4-3 (contours)

Example 1: Horsehead

Measure layering structure – **p-v diagrams**:

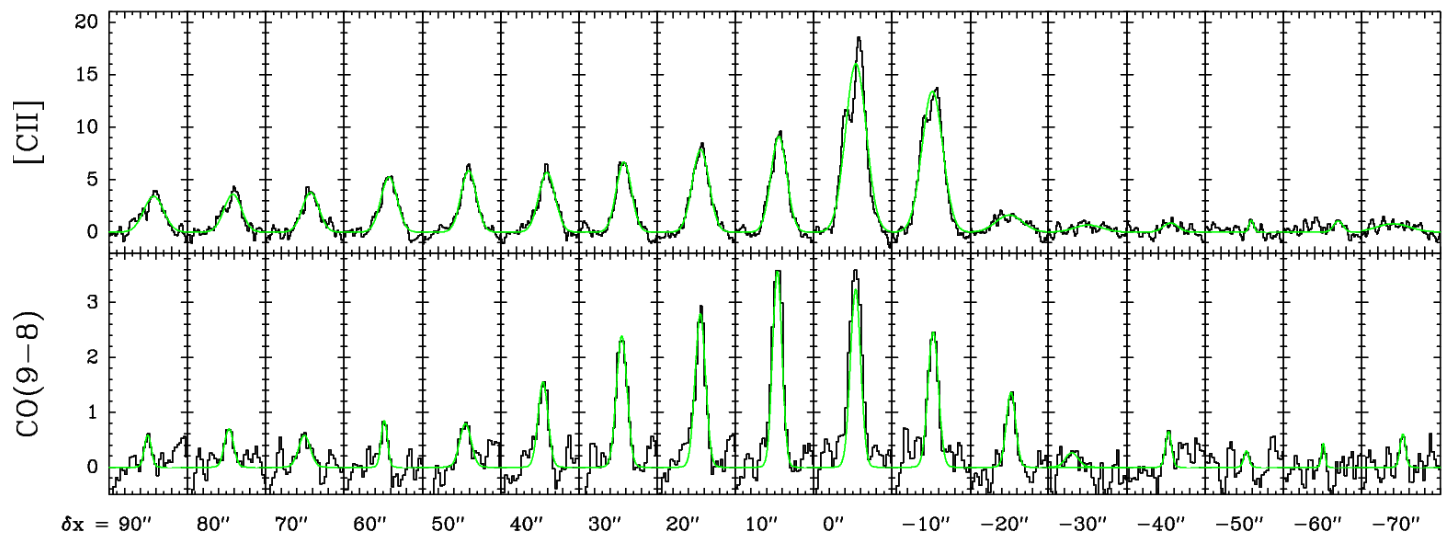




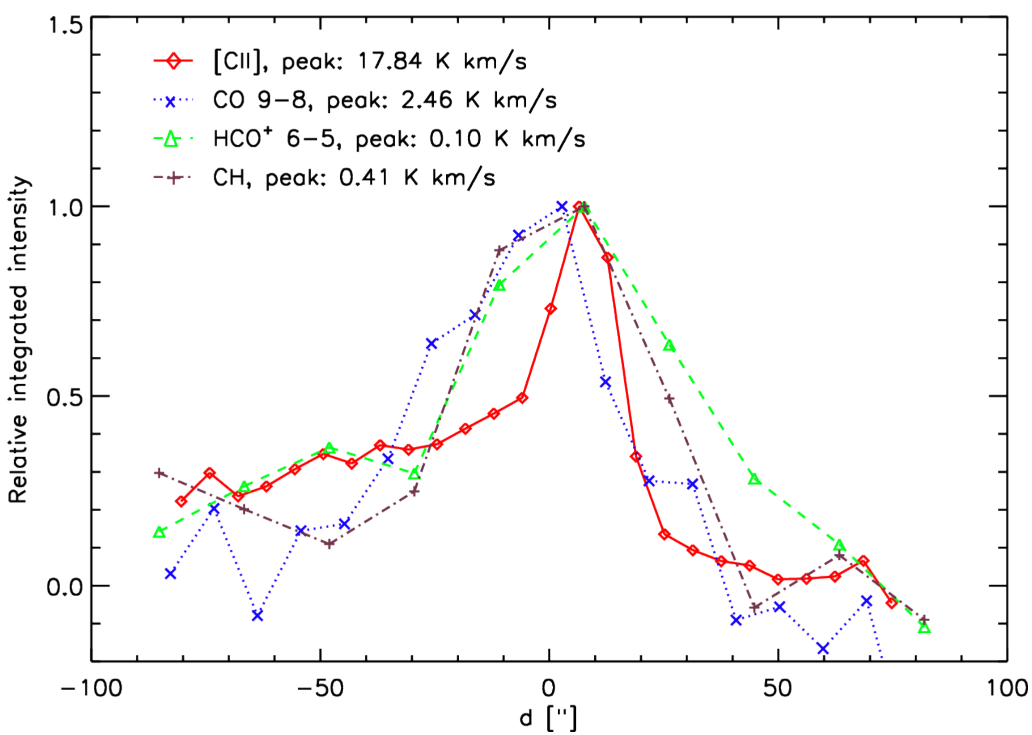
p-v diagrams reveal details of the PDR layering including the dynamical structure

Interpret line parameters

Fit of line profiles along the cut:



Intensity profiles:



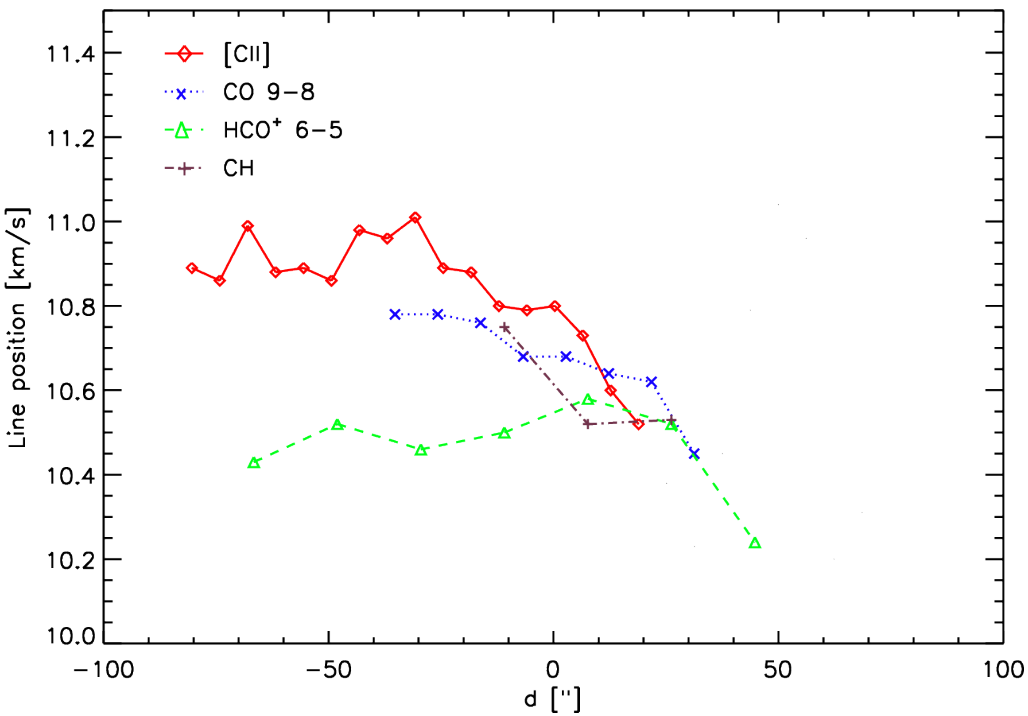
- Stratified chemical structure
- Layering $C^+ \rightarrow HCO^+ \rightarrow CO$
- CH very extended
- C^+ in sharp surface layer

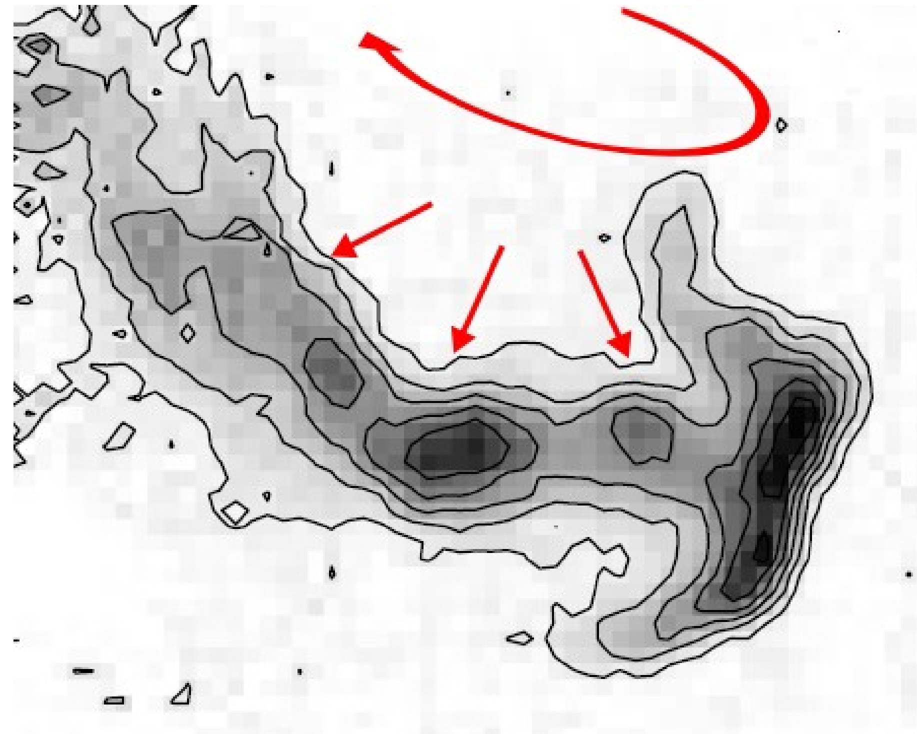
Only surprise:

- Abundant H_2O in gas phase

Interpret line parameters

Velocity structure from p-v diagrams:





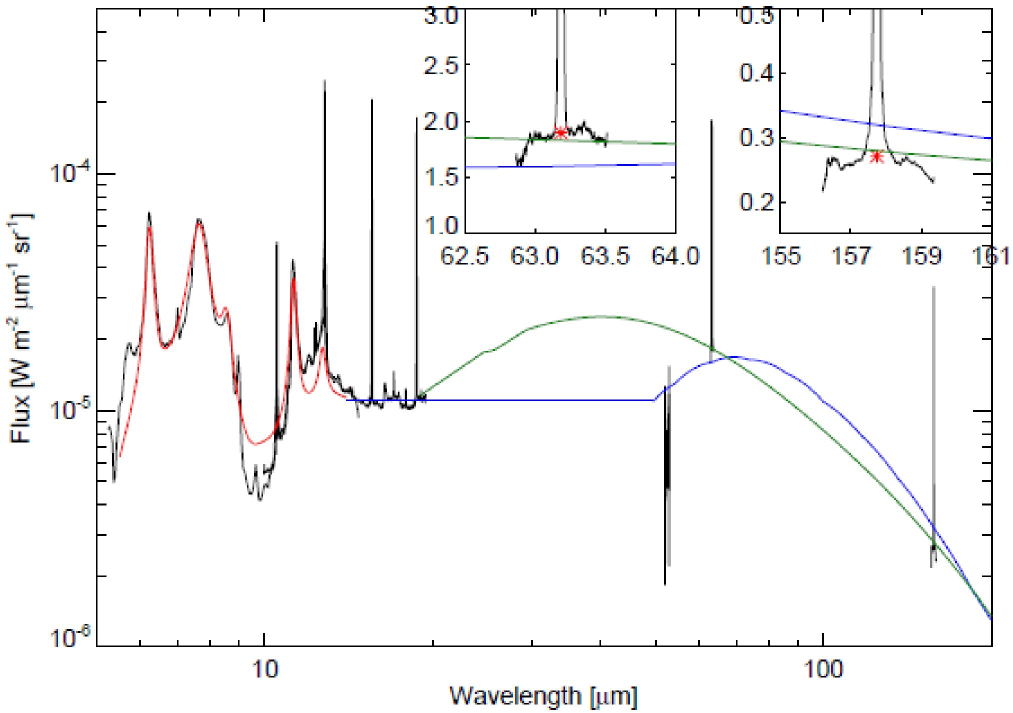
Line center velocities:
- Gradient along the neck
- Offset between [CII] and high-density tracers

Consistent with dynamical picture of Hily-Blant et al. (2005):
- Rotation of large-scale structure
- C^+ accelerated by radiation pressure

(see talk by J. Pety)

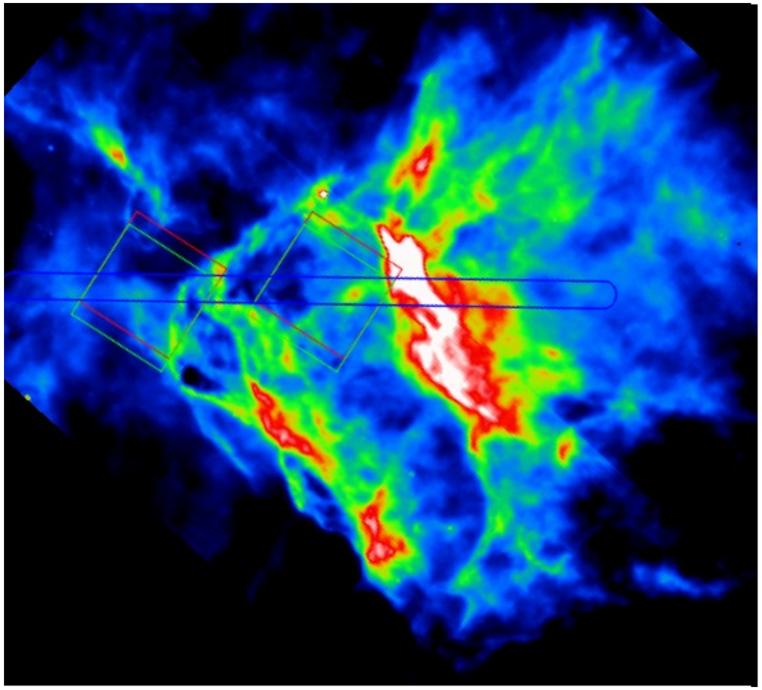
Example 2: Carina North

Energy balance in PDR (multiple interfaces)

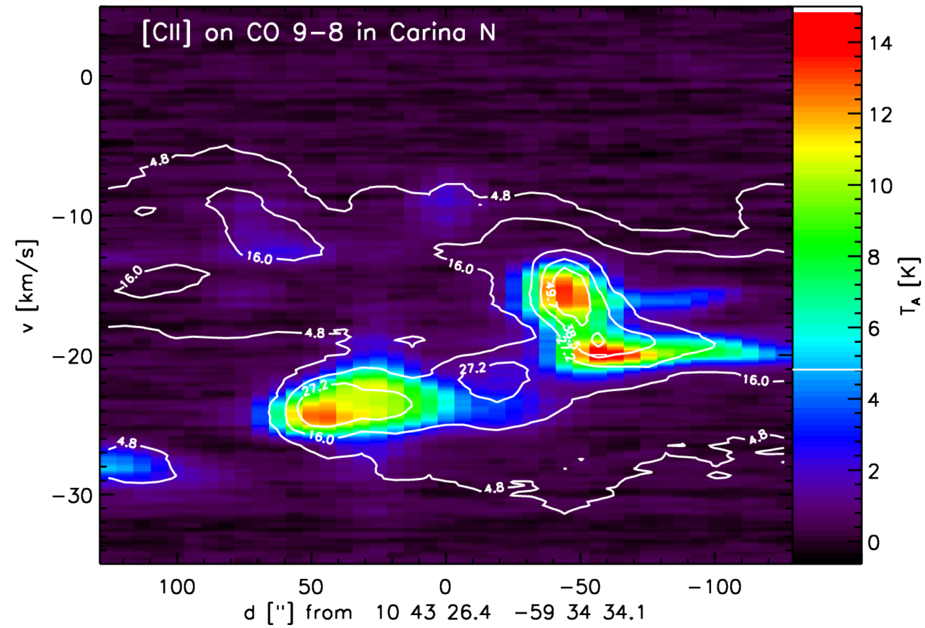


Combined fit of Spitzer-IRS, PACS, and HIFI spectra to determine total IR flux

- remaining uncertainty due to gap between Spitzer IRS and PACS



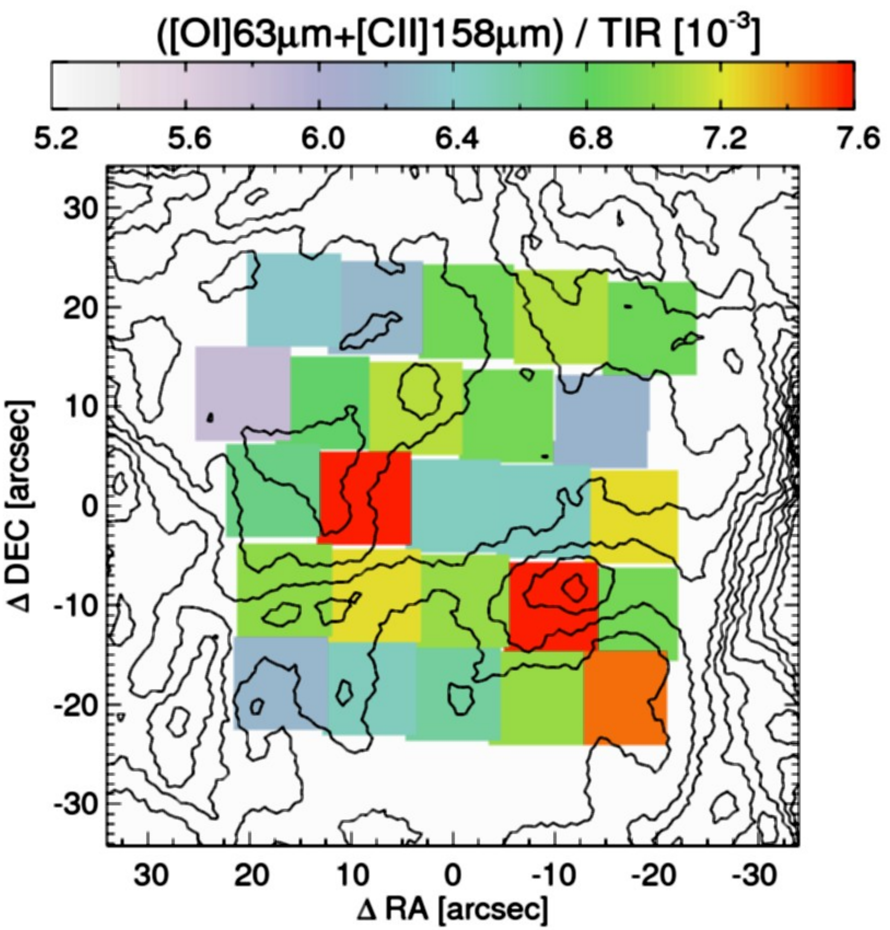
Cut through Carina North PDR



Interfaces seen as clumps in [CII] (contour) and CO 9-8 pv-diagram

Gas heating efficiency

Comparison of line and dust emission in the Carina North PDR:



Contours: 8μm flux

- Gas heating efficiency > 0.5%
- IRS spectra can be decomposed to determine fraction of neutral and ionized PAHs

Dense clumps:

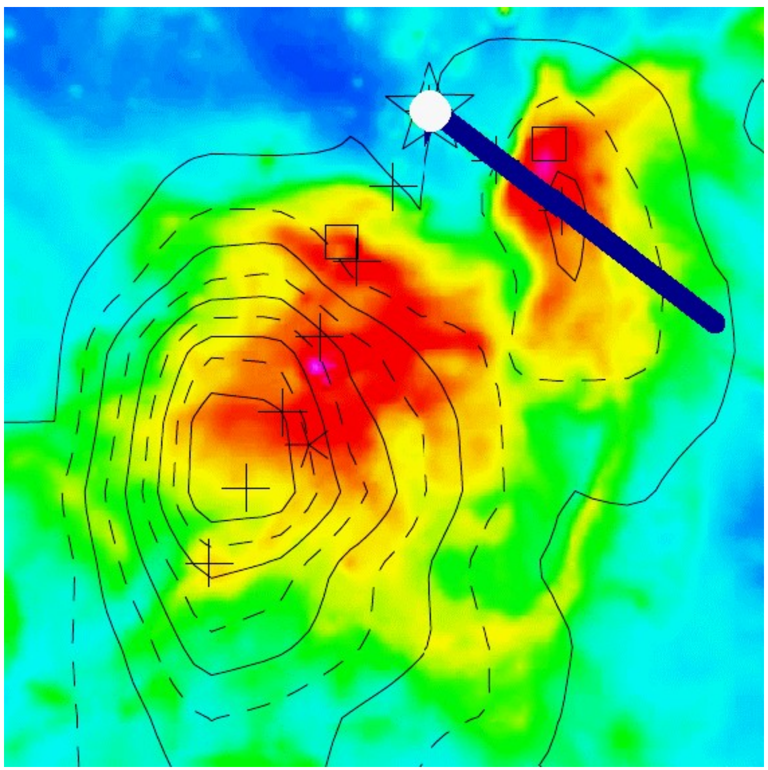
→ fraction of PAH^+ ↓

→ photo-electric heating efficiency ↑

see poster by Okada et al.

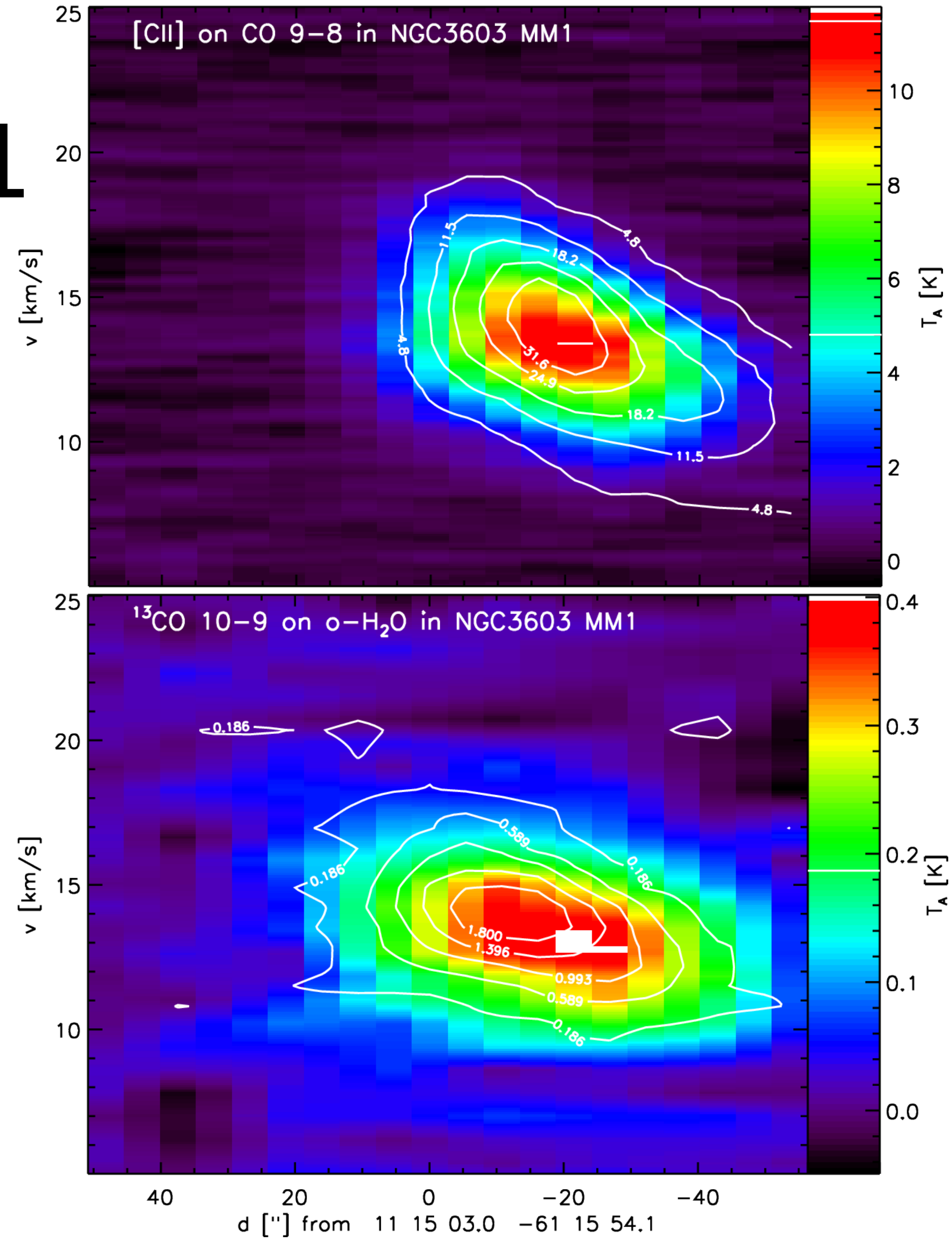
Example 3: NGC3603 MM1

Velocity structure from p-v diagrams:



Observed cuts in NGC3603 overlaid on Spitzer 8µm

Velocity gradient across the core



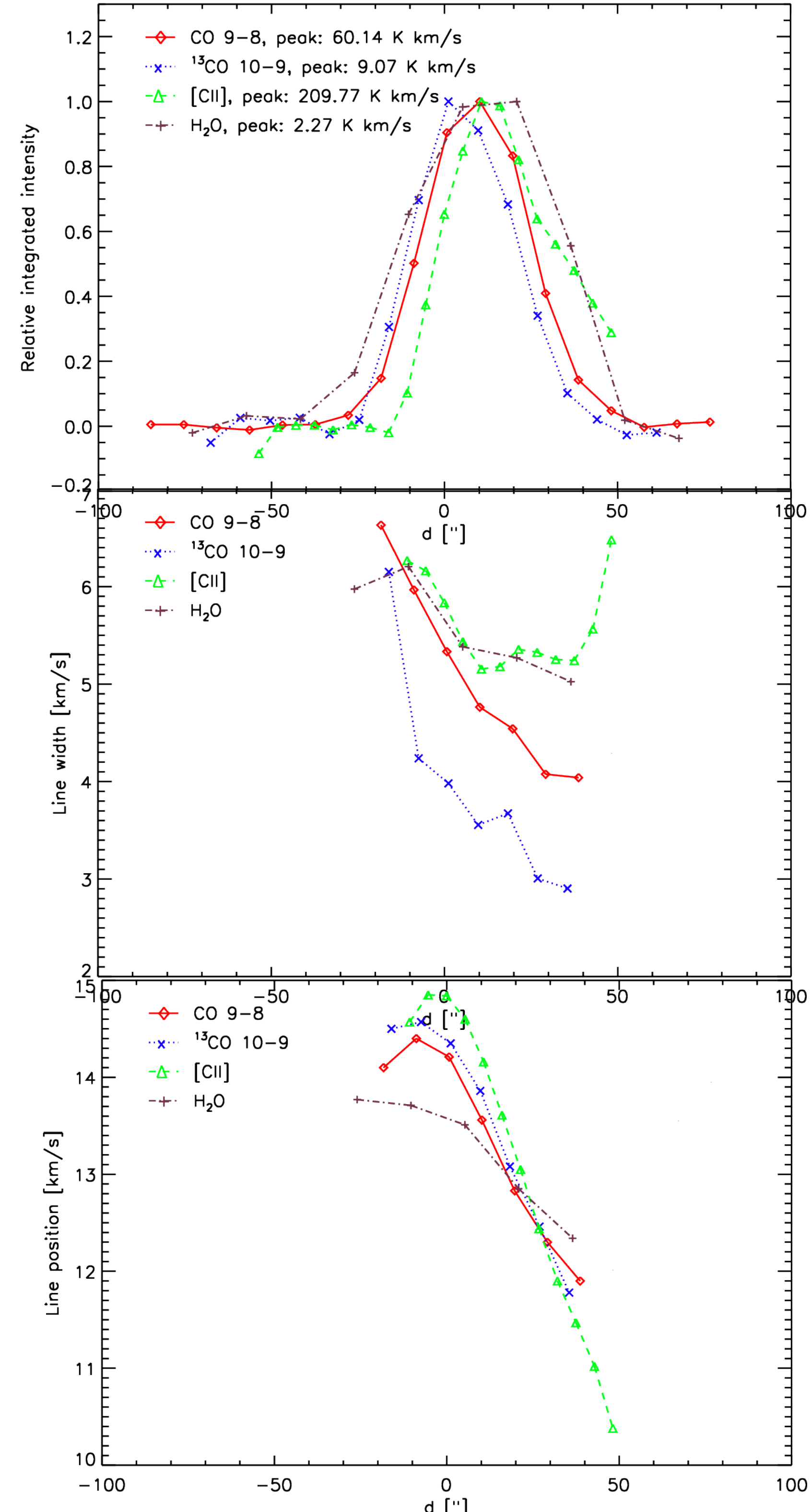
p-v diagrams:
Top: CO 9-8 (colors) + [CII] (contours).
Bottom: o-H_2O (colors) + ^{13}CO 10-9 (contours).

NGC3603 MM1

- Chemical layering partially inverted!
  - [CII] peaks deeper in the core than CO and ^{13}CO
- Broadening of the all lines at surface
- [CII] is red-shifted relative to molecular tracers
- Long turbulent [CII] tail of material "behind" the core

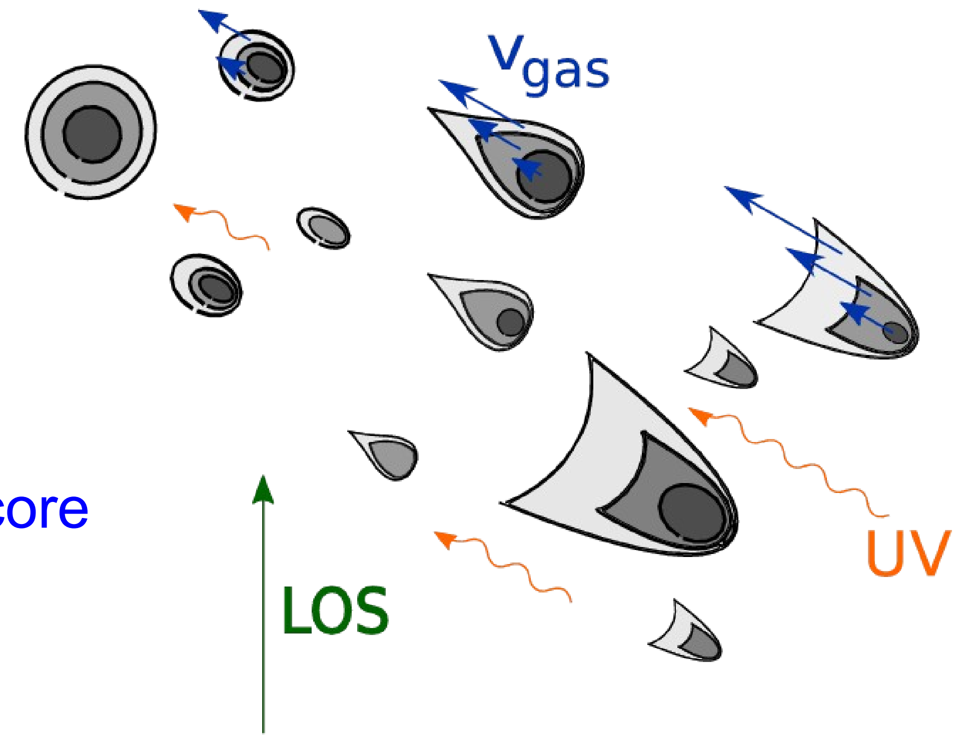
→ C^+ must be blown from the surface into a clumpy medium

- ➔ Redshifted profiles → affected material sits behind the cluster
- ➔ The 4km/s gradient along the core measures compression!

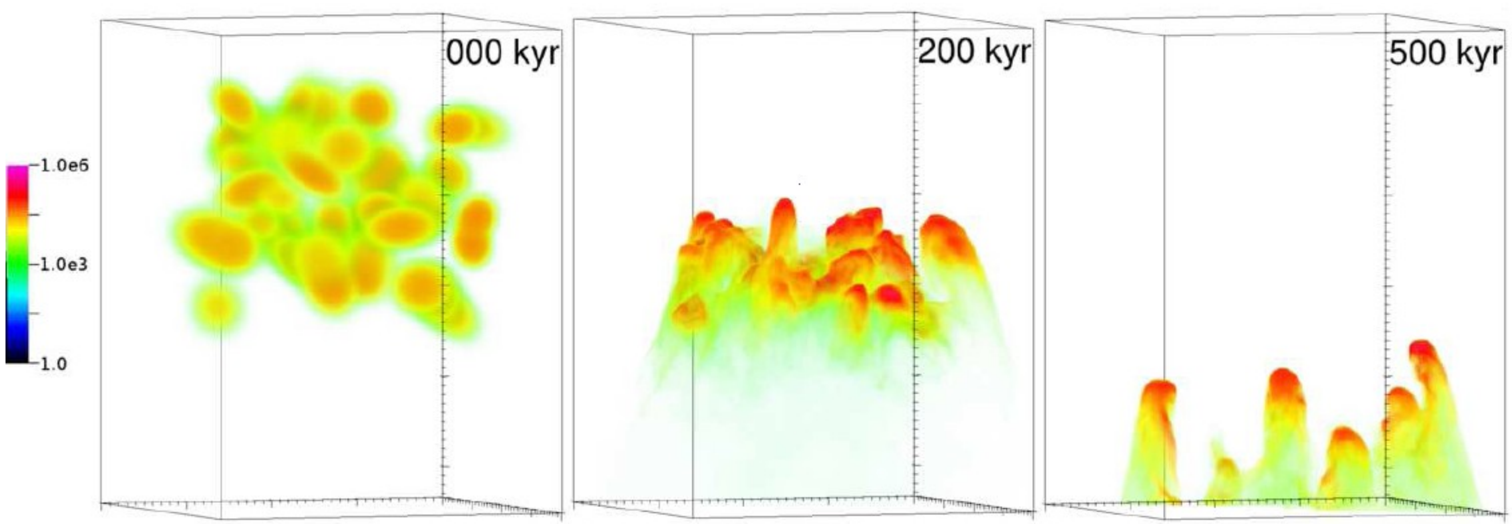


Interpretation

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

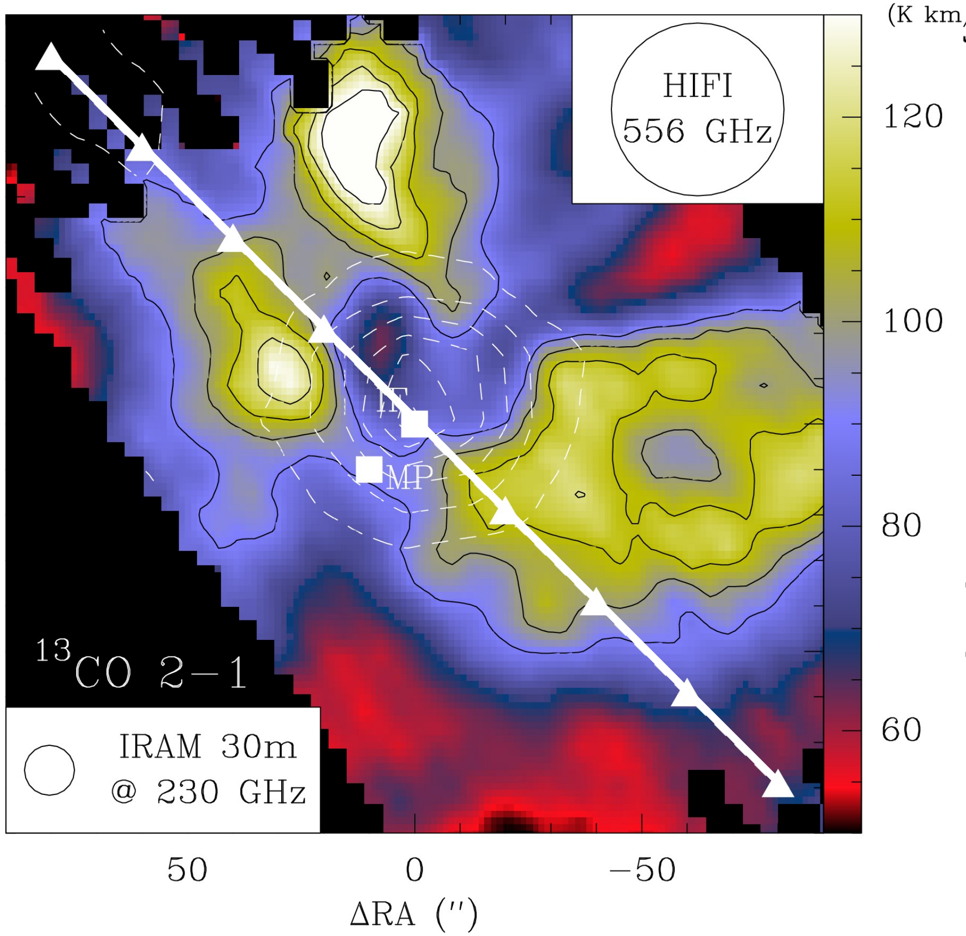


Compare: Mackey & Lim (MNRAS submitted)

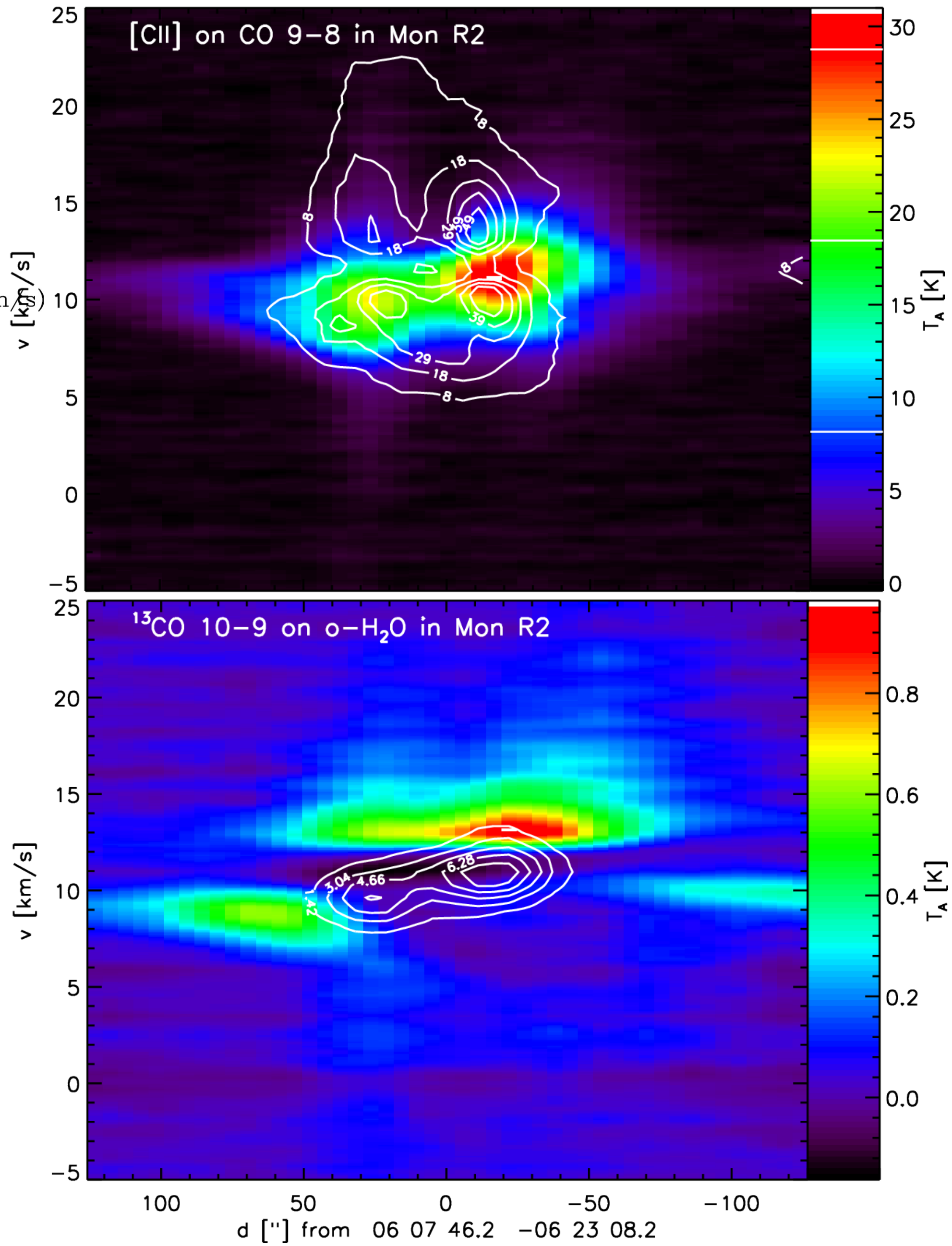


→ Pillar formation

Example 4: Mon R2



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

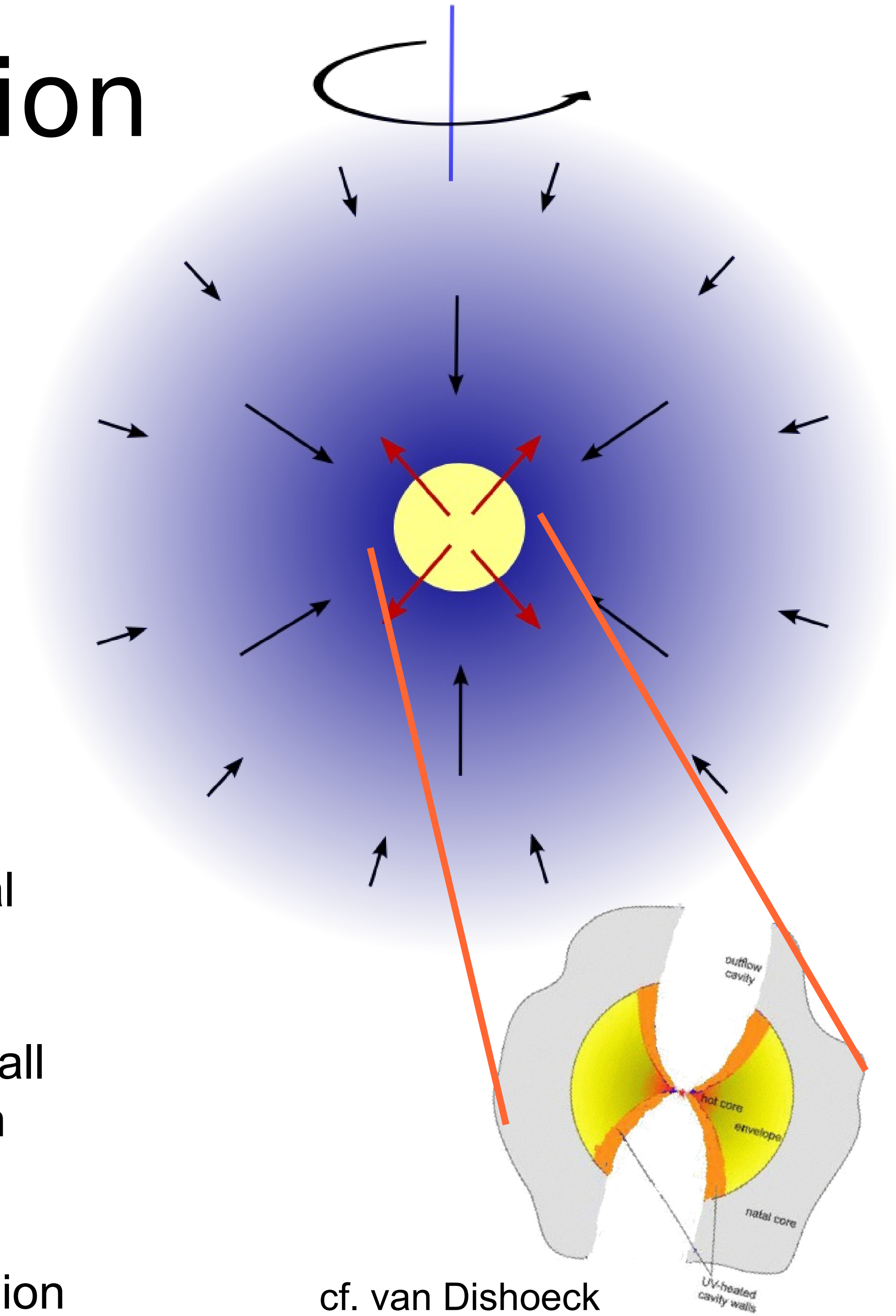


p-v diagrams:
Top: CO 9-8 (colors) + [CII] (contours).
Bottom: o-H_2O (colors) + ^{13}CO 10-9 (contours).

Interpretation

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

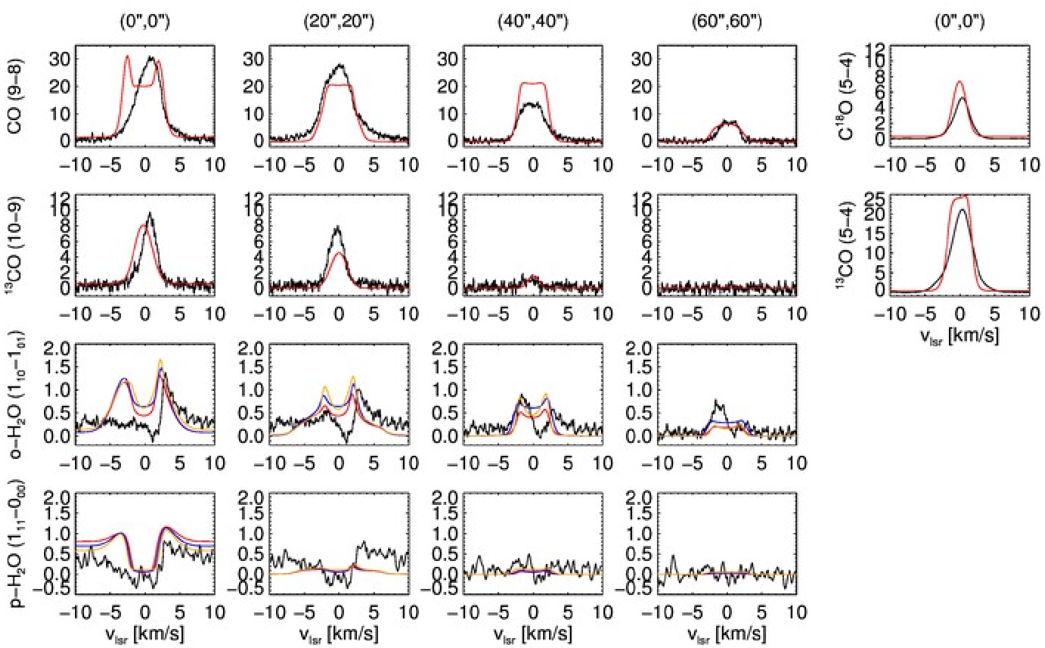
- CO 9-8 shows the PDR
  - Illumiated dense molecular material
- Water in absorption for low velocities, red-shifted velocities in emission
  - Emission from backside or core-infall
- Double-peaked [CII] profile mainly from walls of HII region
  - Wings trace ionized flow
  - Some self-absorption in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



cf. van Dishoeck

Multi-line model fit

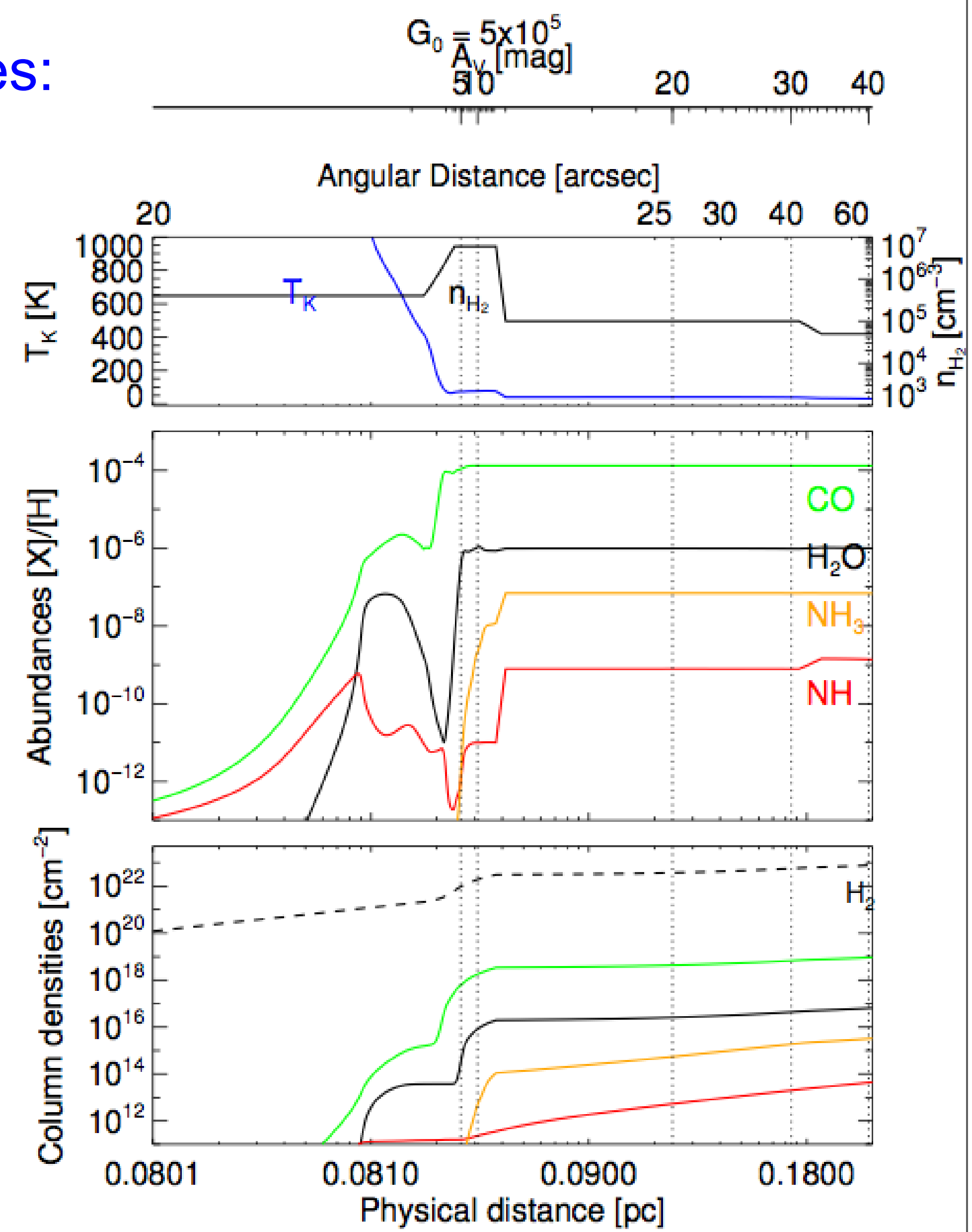
Combine HIFI and ground-based profiles:



1-D PDR and radiative transfer model:

- High-velocity expanding layer:
  T > 100K, $X(o\text{-}H_2O) \sim 10^{-7}$
- Low-velocity cloud:
  T < 100K, $X(o\text{-}H_2O) \sim 10^{-8}$

(Pilleri et al., submitted)



Summary

- Herschel has proven to be the ideal tool to observe the chemical stratification in PDRs
- Big step towards complete chemical inventory and detailed resolution of the energy balance
- Radiation pressure driven PDR dynamics is complex
  - Pressure jump at the surface confirmed
  - First direct observation of radiative core compression
    - Pillar formation → star-formation triggering ?
  - Significant dispersion of gas → SF efficiency low
  - No evaporation flows!
  - No indication of turbulent stirring through radiation
- More data analysis to come (too many spectra for the models)