Observations of Photodissociation Regions

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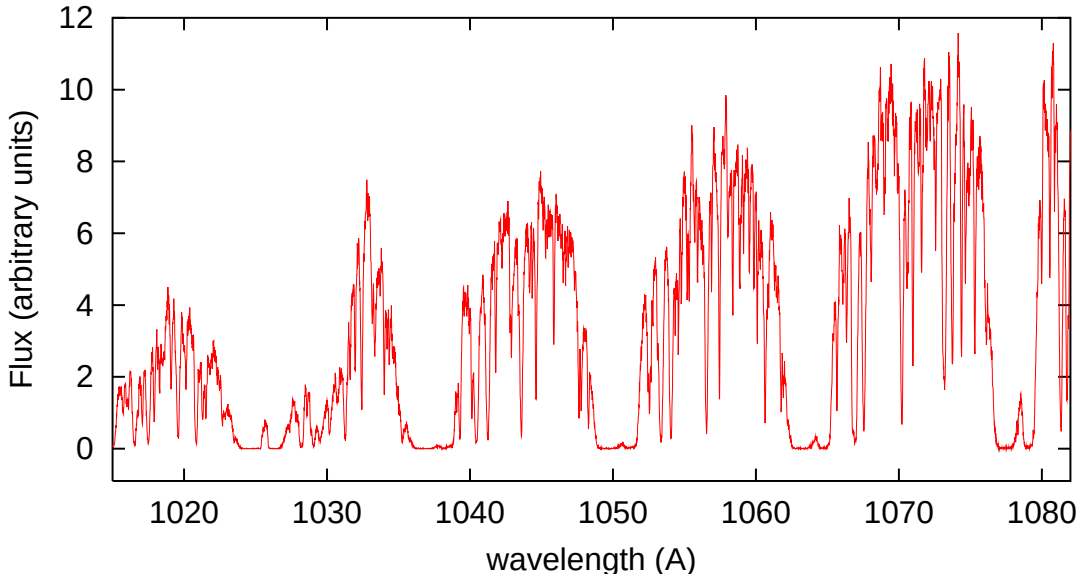
Observations

- Images
- Spectra , single position, maps
- Polarisation

What for ?

- Structure and Geometry
- Molecules as probes of physical conditions
- Molecular abundances, spatial distribution
- Line and continuum intensities versus predictions
- Grain properties
- Gas dynamics

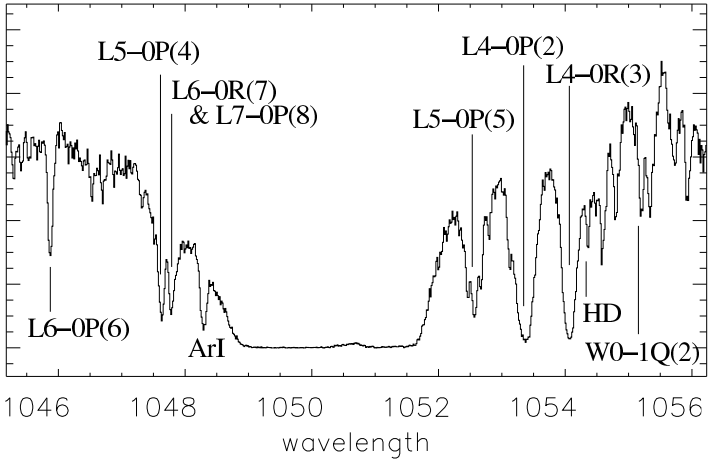
Diffuse interstellar clouds : UV and visible absorption spectroscopy



HD34078 observed with FUSE, Le Petit F. et al. 2002

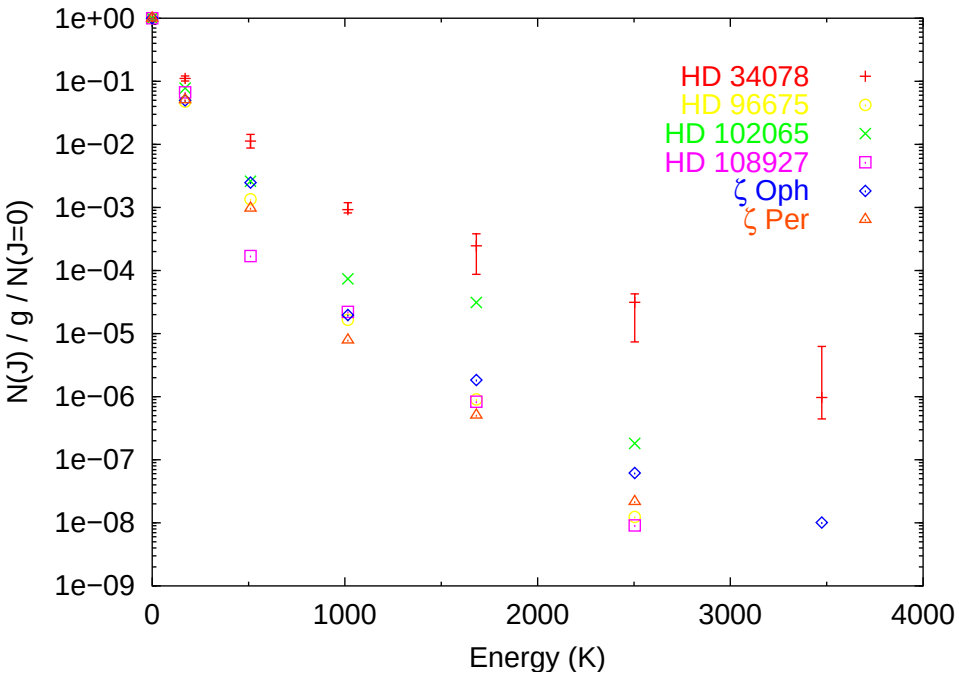
- Accurate determination of column densities for atoms, ions and molecules, except for species in the "flat" section of the curve of growth (HD)
- Accurate determination of the excitation for carbon, H_2, C_2 ...
- Simultaneous constraints on physical conditions and abundances
- No information on the geometry.

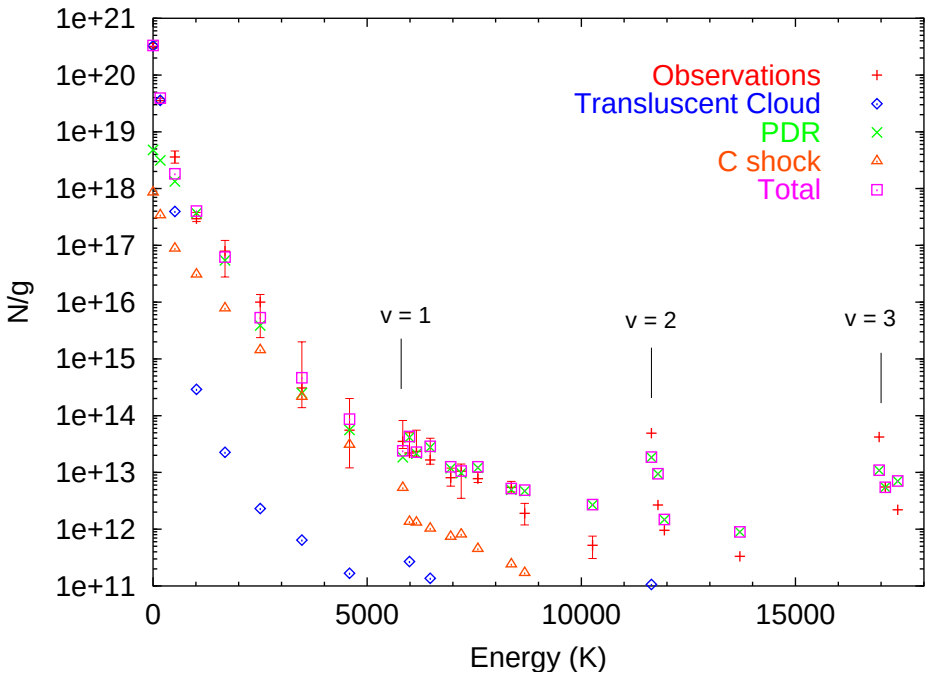
far UV H_2 lines



HD34078 observed with FUSE, Le Petit F. et al. 2002

H_2 excitation





Le Petit F. et al. 2002

HD34078 : very high excitation H_2, different from the classical diffuse clouds

$\Rightarrow$ Composite models with 3 components.

$\Rightarrow$ CO observations (Feb. 2004) for the geometry and structure.

HD102065, combining absorption spectroscopy and large scale imaging

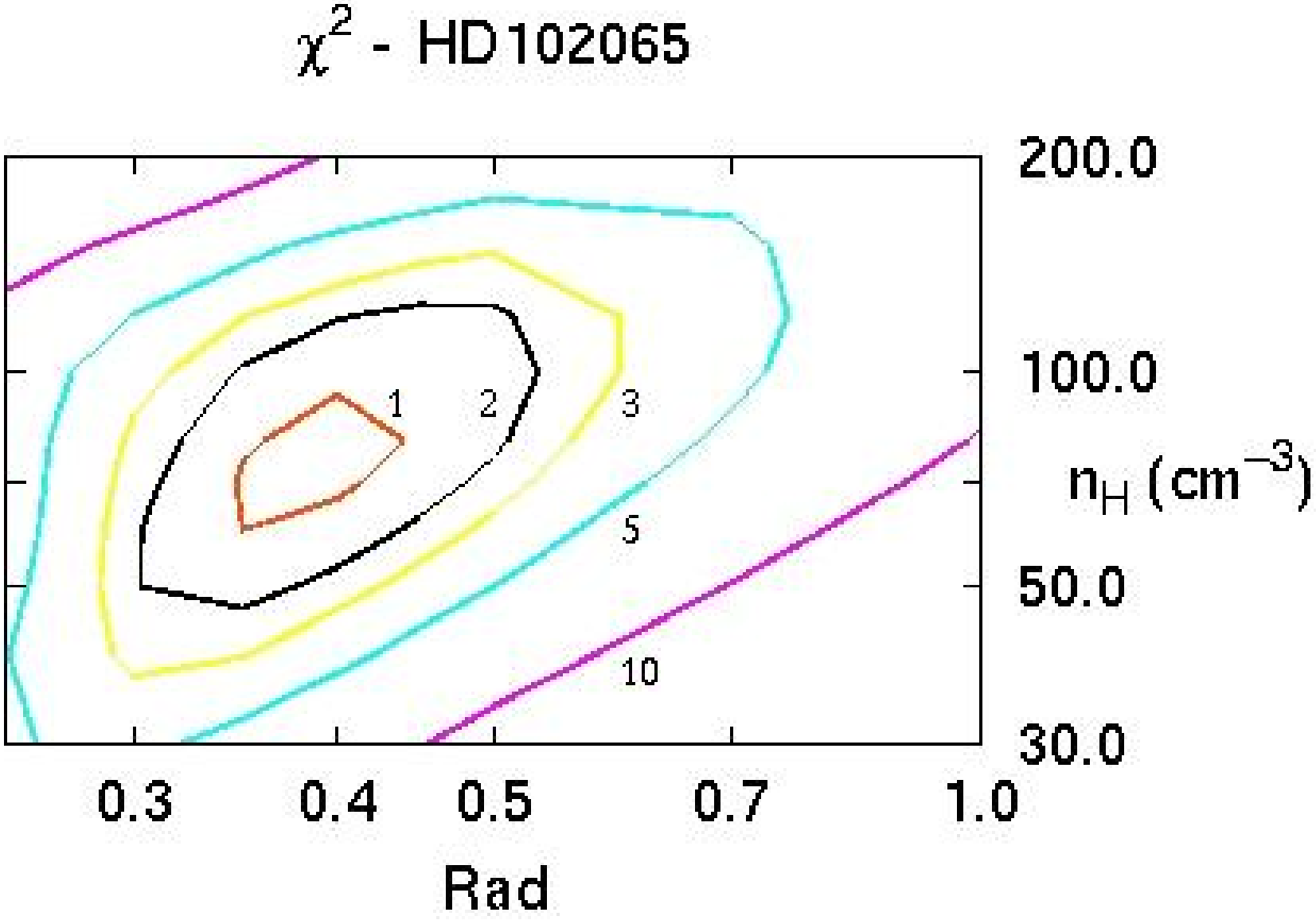
B9 star, far from the interstellar cloud, $A_v = 0.67$, FUSE & HST/STIS data. Dust properties from IUE and IRAS. Standard Interstellar abundances (ζOph).

$\frac{N(CO)}{N(H_2)}$	$\frac{N(C_{at})}{N(C_{tot})}$	$\frac{N(C_{J=1})}{N(C_{at})}$	$\frac{N(C_{J=2})}{N(C_{at})}$	f	O/P	$I(C^+)$
$1.5\,10^{-7}$	$4.2\,10^{-3}$	0.16	0.024	0.69	0.7	$2.8\,10^{-6}$
$1.75\,10^{-8}$	$1.5\,10^{-3}$	0.07	0.01	0.12	0.12	$8.5\,10^{-7}$

The gas density n_H and radiation field χ are obtained from a χ^2 minimisation, using

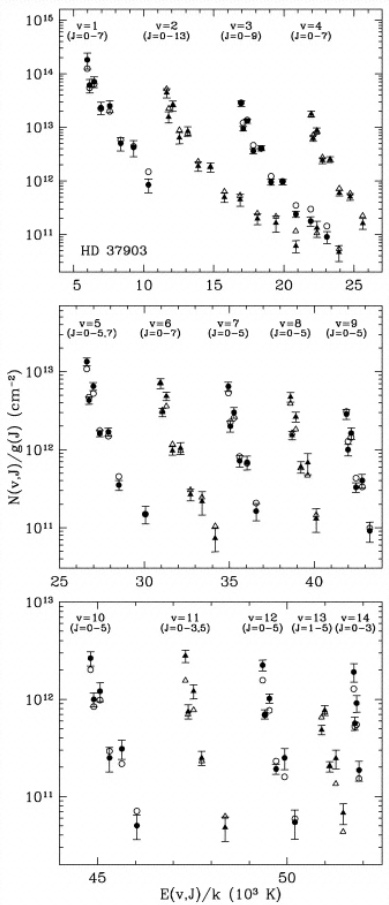
$$\chi^2 = \frac{1}{7} \sum \left(\frac{X_{obs} - X_{mod}}{\sigma_X} \right)^2$$

HD102065



Nehme C., Le Bourlot J., Boulanger F., Gry C., in preparation

excited H_2, HD37903 in NGC 2023



Meyer et al. 2001, model by Draine & Bertoldi

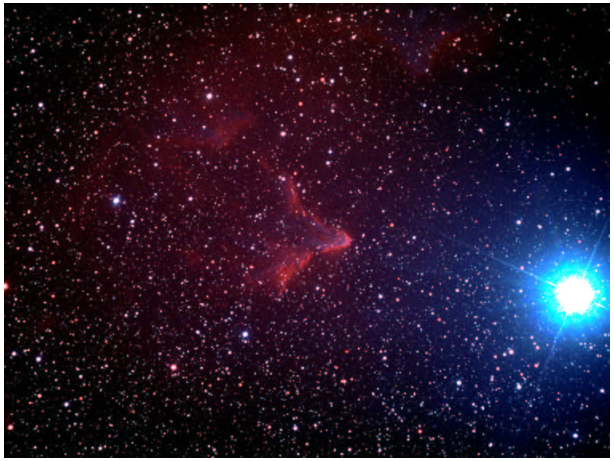
H_3^+

- Detection in diffuse clouds, ζPer (Mc Call et al. 2003)
- Very high Cosmic rays ionisation rate ? x 40 "standard rate" ?
- Source structure (diffuse gas + dense cloudlet ; Le Petit et al. 2004)

$\Rightarrow$ Information on the source geometry and spatial structure is needed.

The complex (multi phase) ISM structure needs to be taken into account.

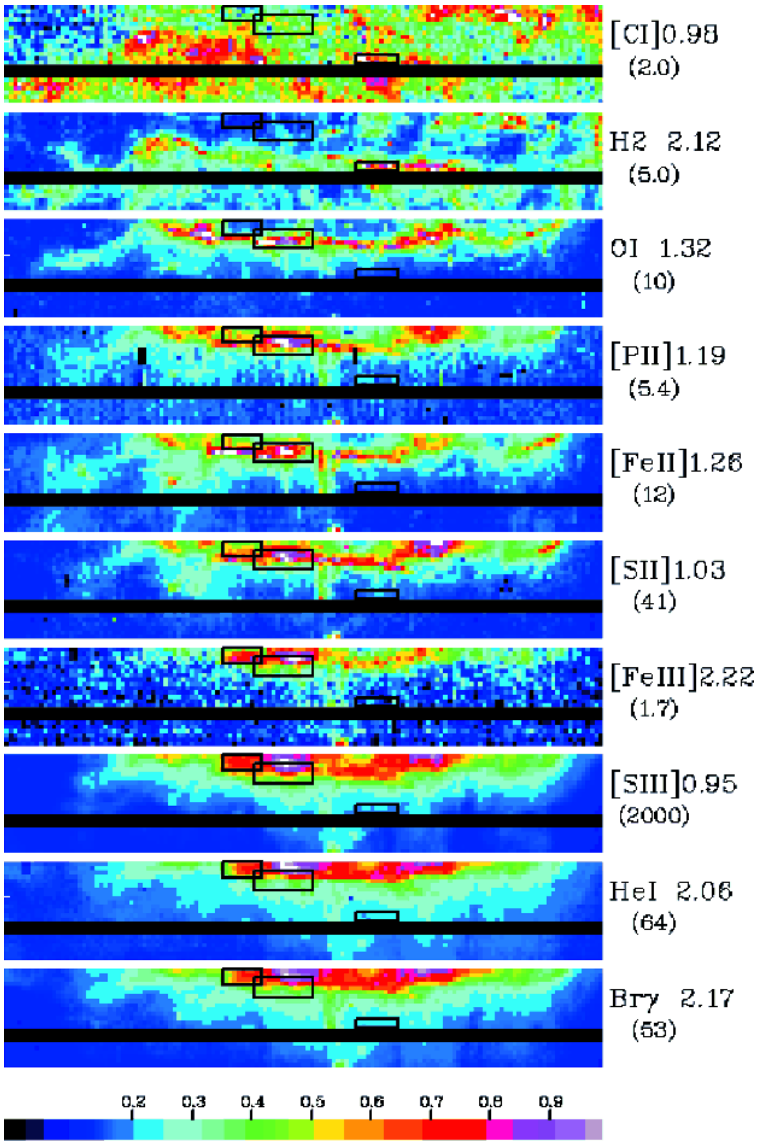
Visible and IR imaging



IC 63 illuminated by γ Cas

- scattered light : source geometry, dust albedo
- Near infrared continuum : scatterred light plus dust emission
- Mid infrared : dust emission, PAH features
- Rich line spectrum, H_2, CI, OI, etc.

The visible-near IR spectrum of the Orion Bar

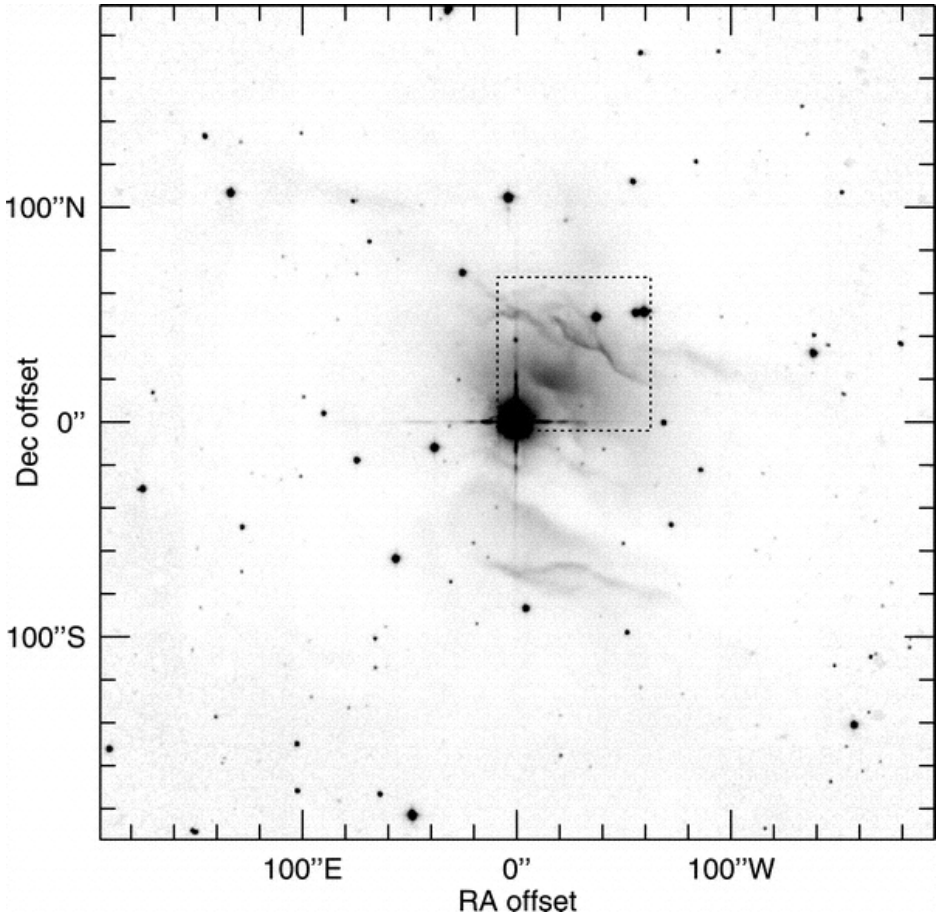


Walmsley et al. 2000, SOFI on NTT

Various tracers, from the ionized gas to the PDR

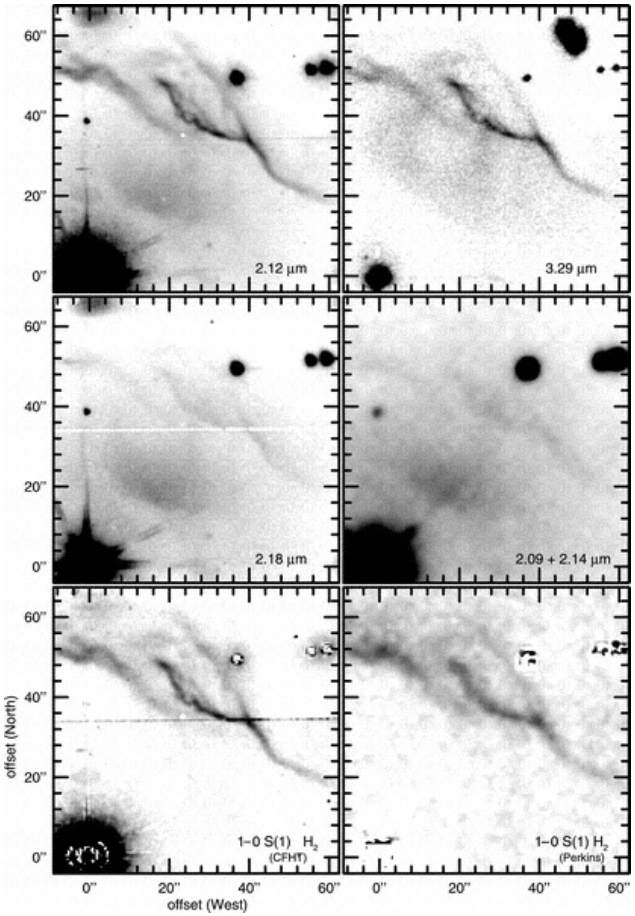
Fluorescence vs collisional excitation depending on the tracers

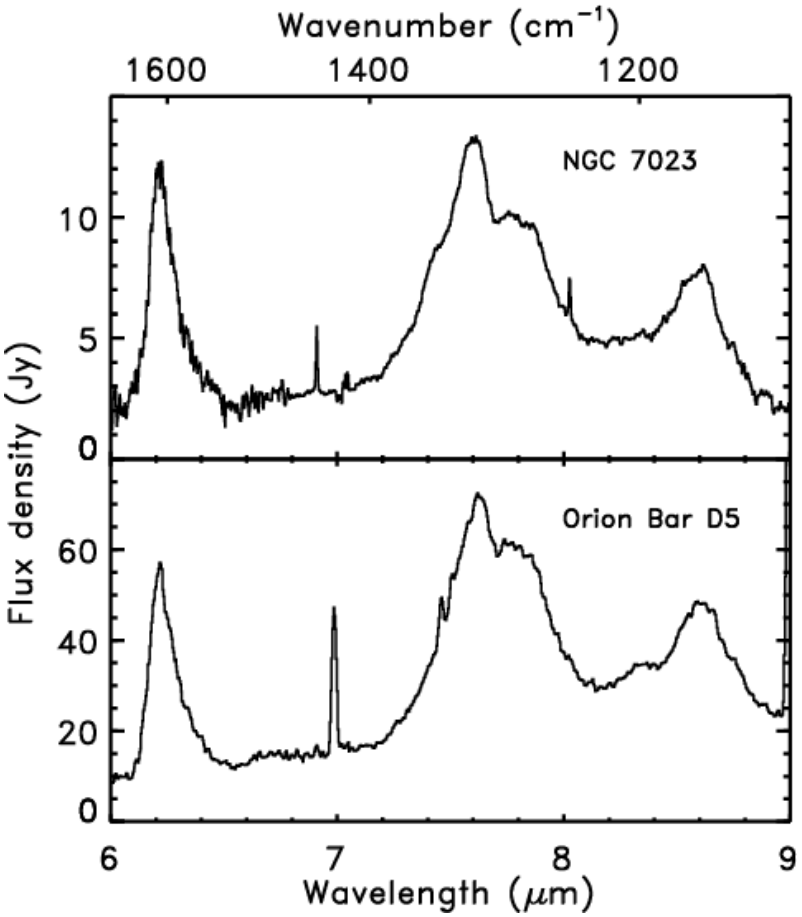
Near IR images : NGC 7023



An & Sellgren, 2003, K' image.

Near IR images NGC 7023





An & Sellgren, 2003; Peeters et al. 2002

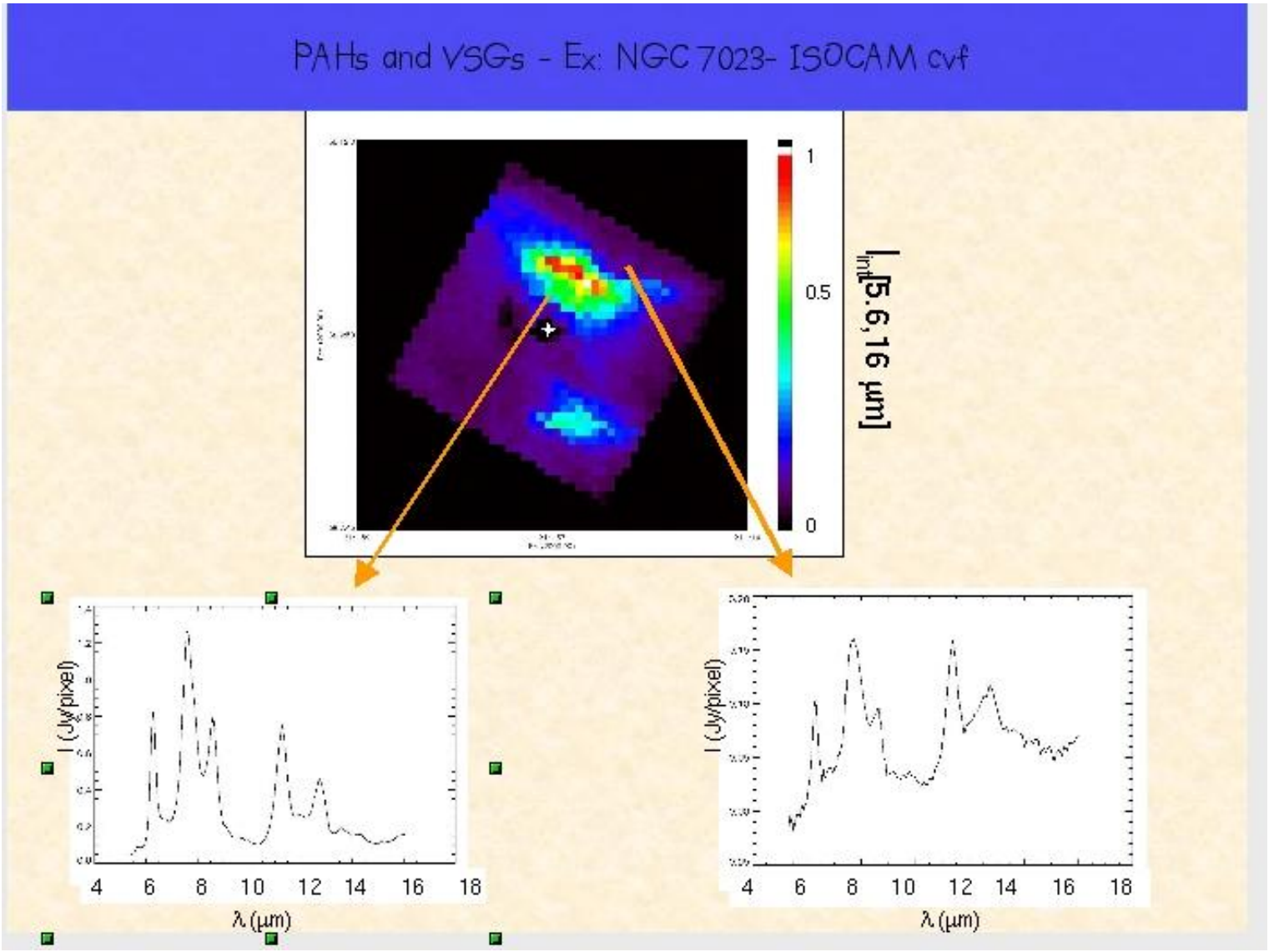
Comparison of the H_2 and dust maps :

- dust properties

- source structure : the separation between H_2 and PAH is sensitive to the gas density

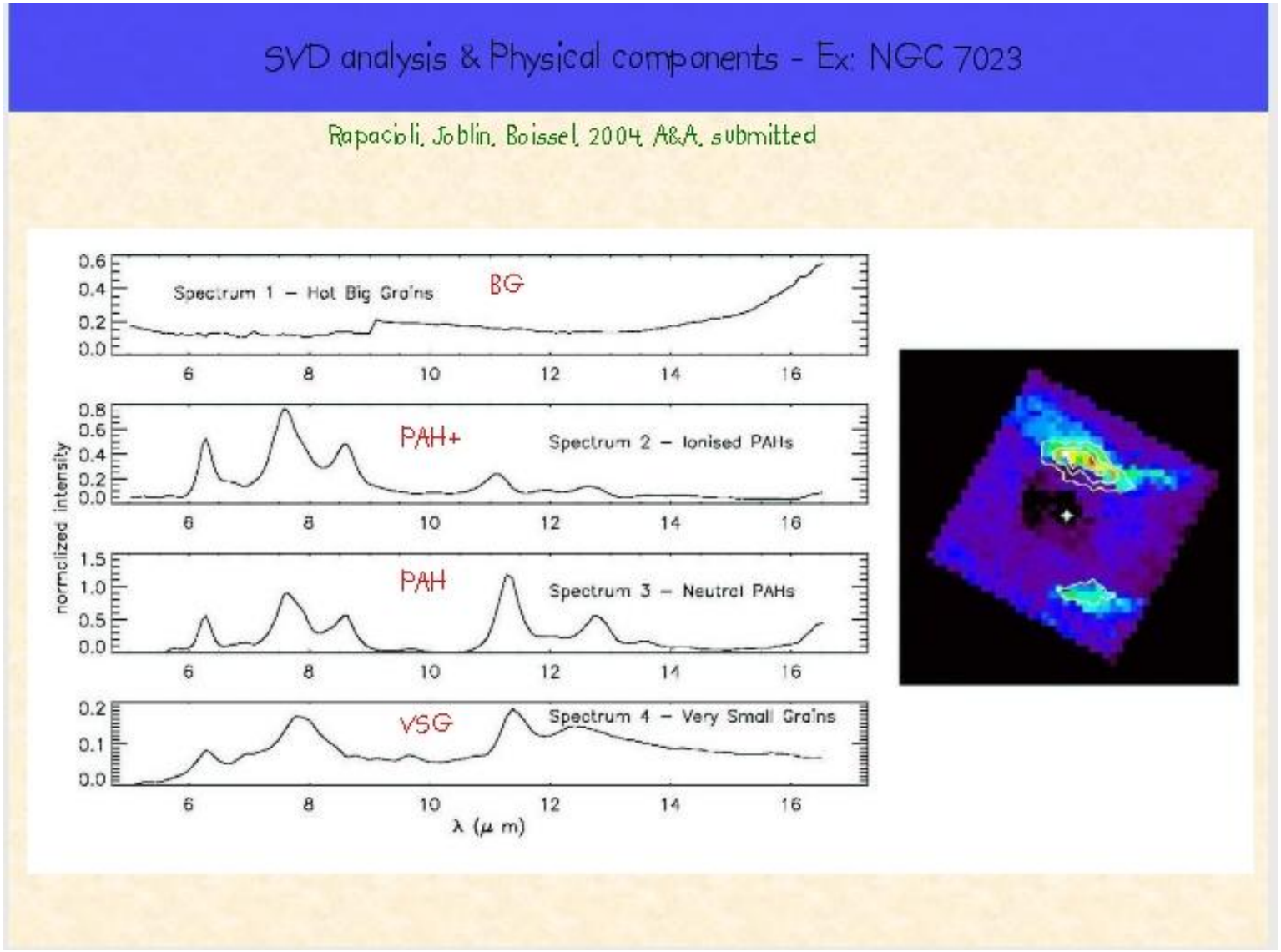
- H_2 formation rate
  Habart et al. 2002, 2004, Noel et al., Abergel et al. 2003, ...

Studying the dust properties, the PAH population in NGC 7023



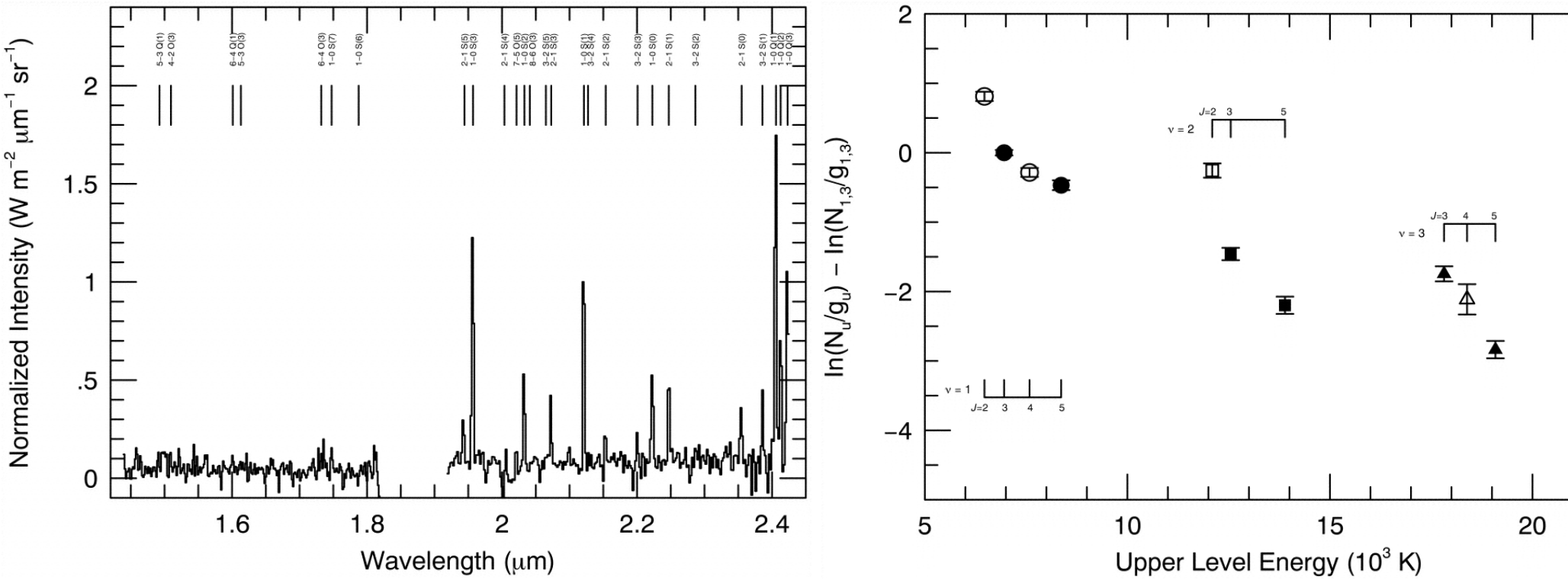
Rappacioli, Joblin et al. 2004, evolution of the mid-IR spectrum as a function of the position in NGC 7023? sampling the PAH population and ionisation

the PAH population in NGC27023



Rappacioli et al. 2004

H_2 excitation in the IR

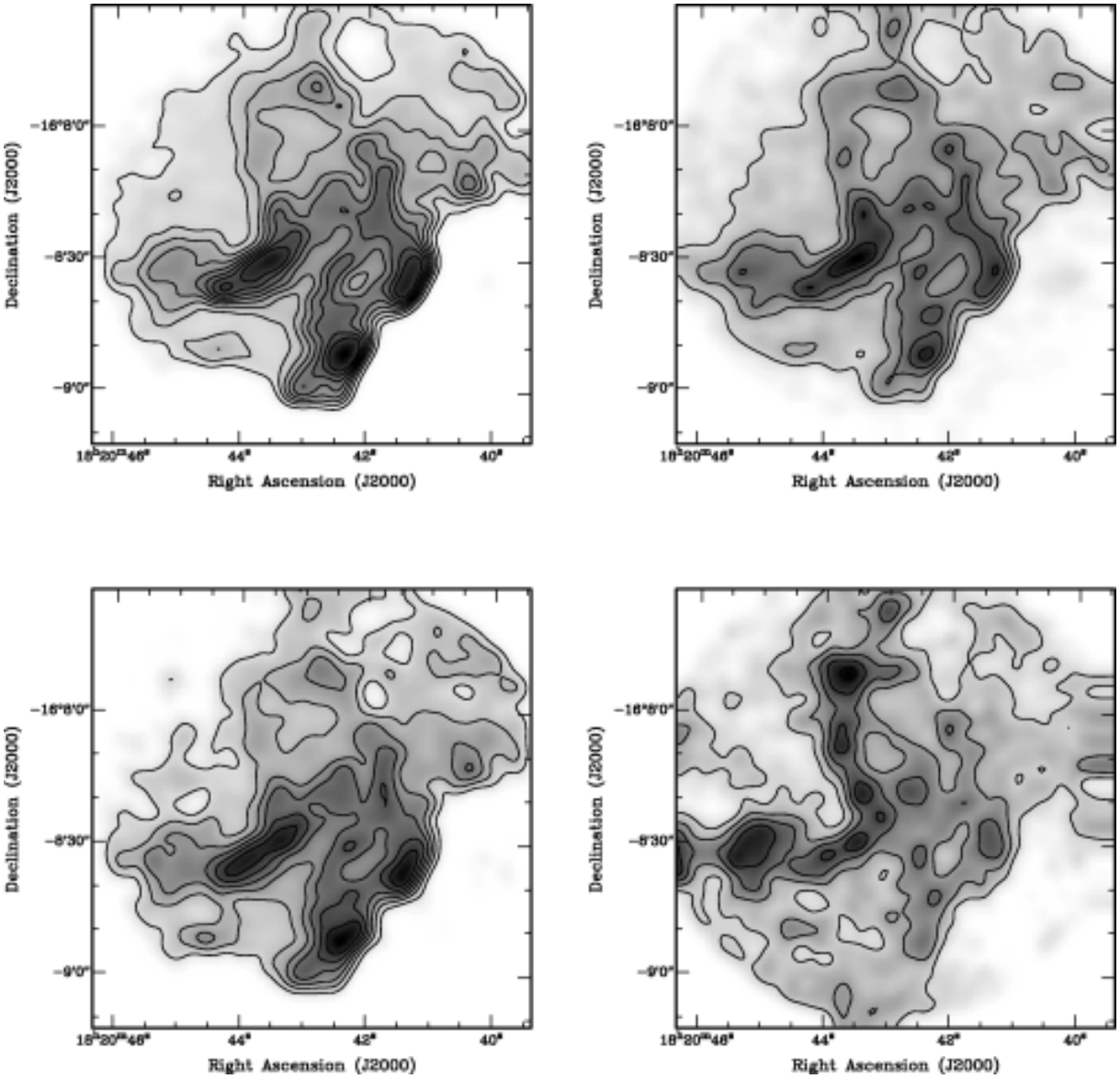


Martini et al. 1997, H_2 lines in the H and K band.

H_2 excitation from the mid-IR spectrum.

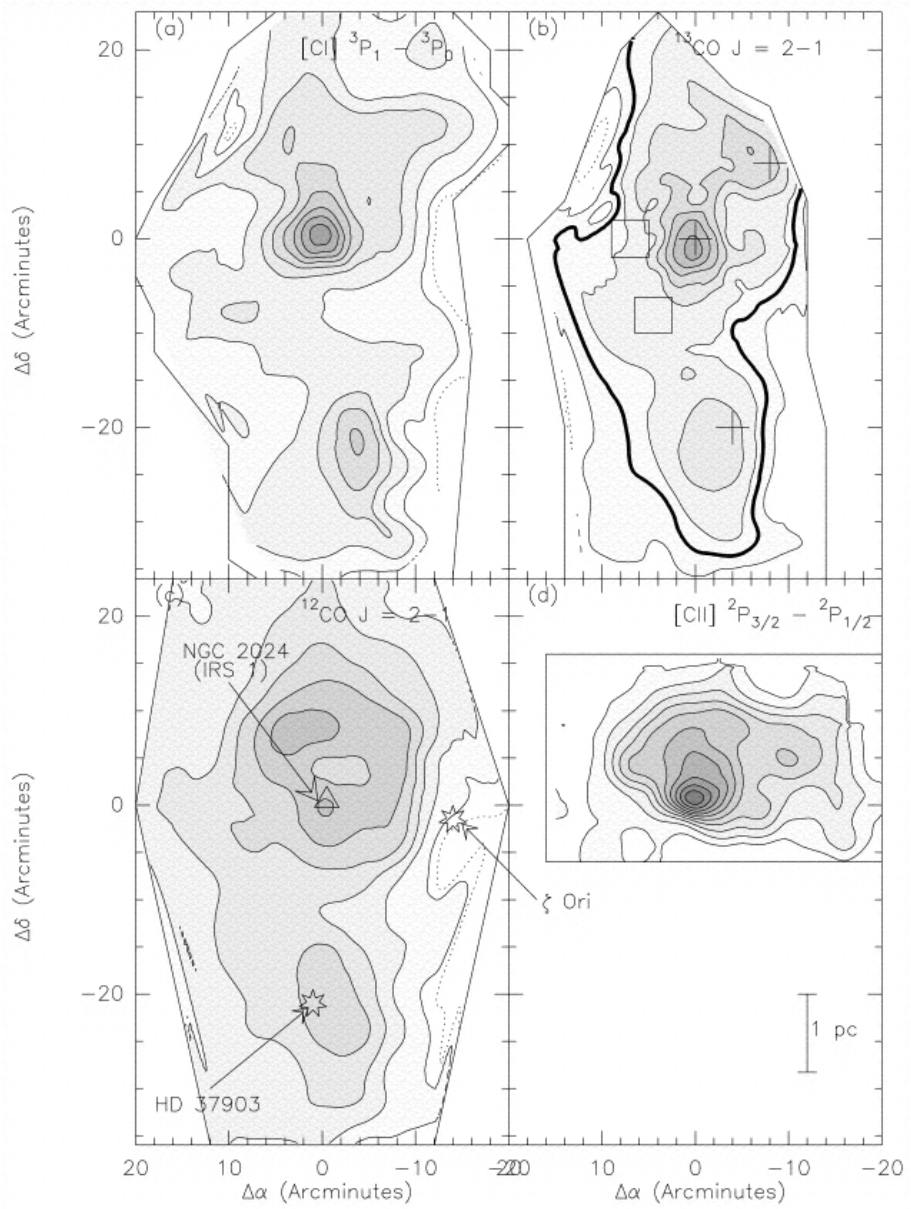
The line ratios are sensitive to the gas density and FUV pumping formation process ? (Burton et al. 2002, emission in v=6 ?)

H_2 formation, M17



Burton et al. 2002, M17SW. clockwise H_2 1-0 S(1) (2.1218) , 2-1 S(1) (2.2233 m), 6-4 O(3) (1.7326) and 1-0 S(7) (1.7480)

Far infrared, submillimeter and millimeter data : Gas cooling, and chemistry

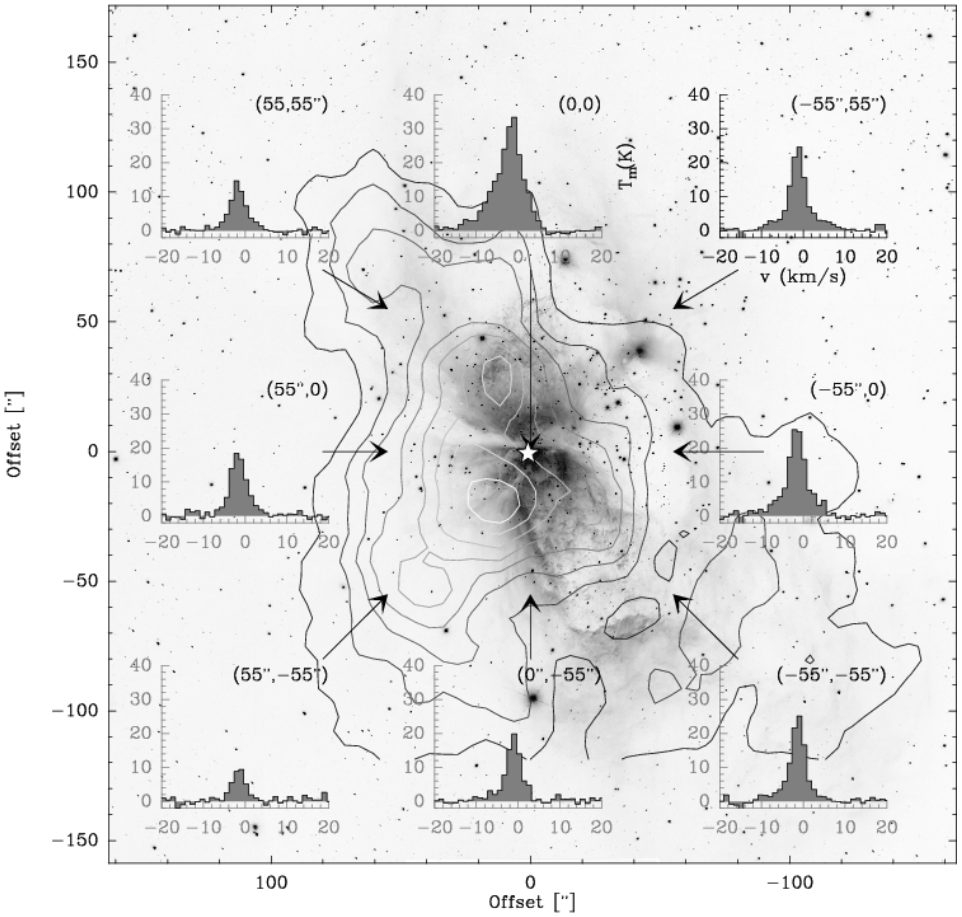


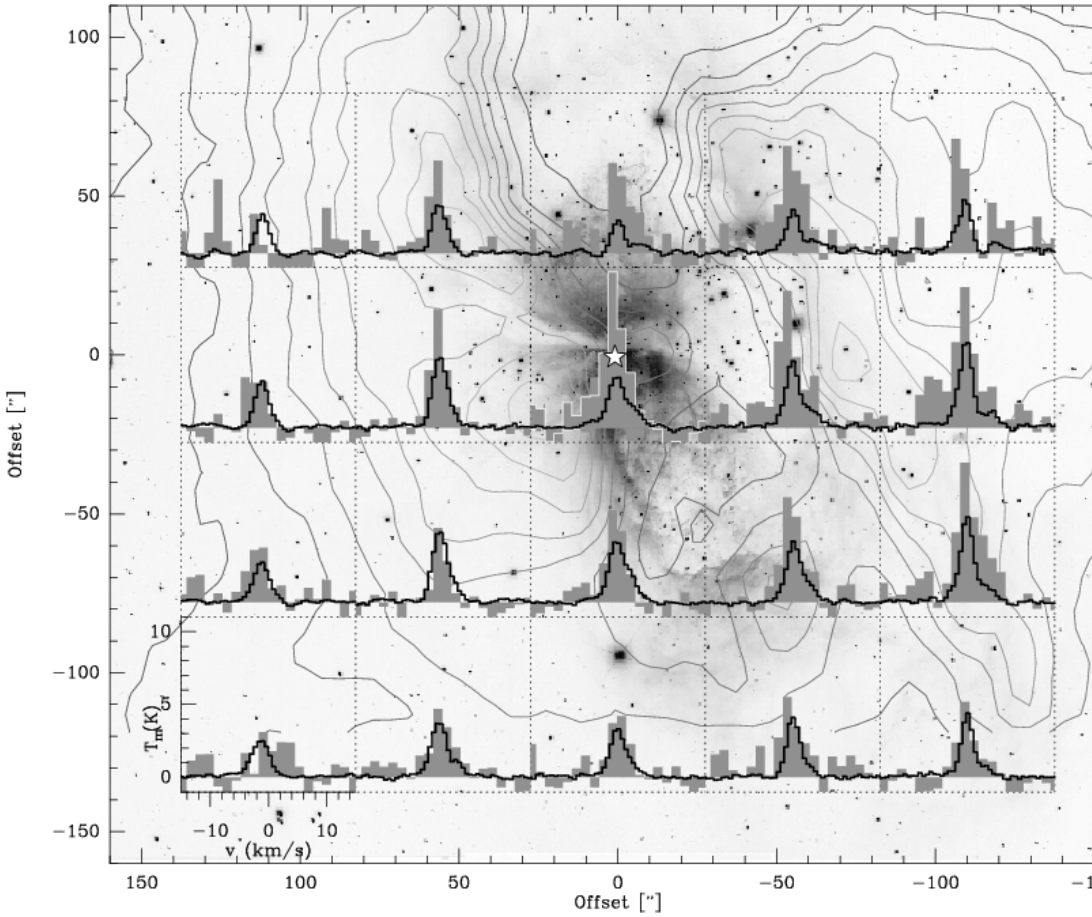
Plume et al. 1999

Far infrared fine structure lines

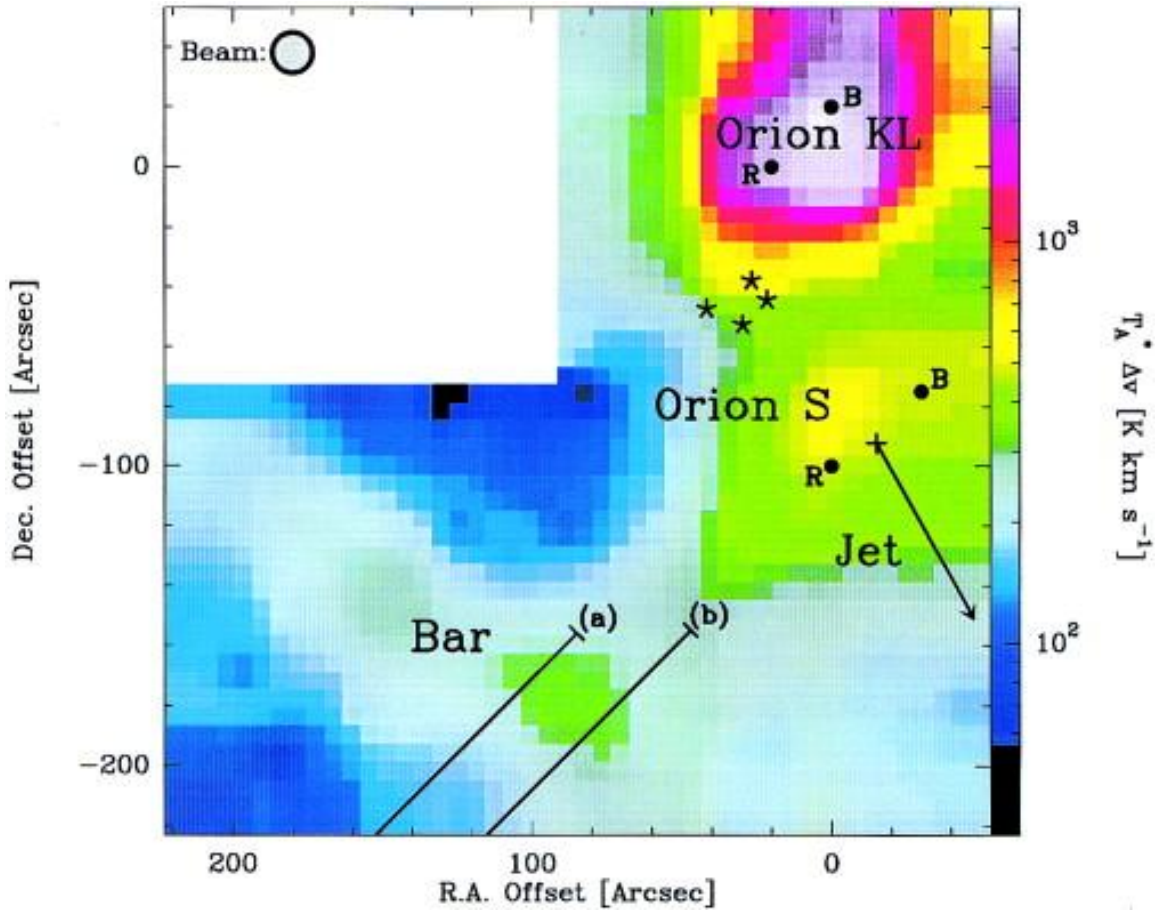
- Gas cooling by the fine structure lines [CII], [OI] in the far infrared
- Line intensities by KAO, ISO data, very few information on line profile. $\Rightarrow$ SOFIA, HERSCHEL
- [CII] is extended in molecular clouds, clumpy structure
- [CII] is one of the main cooling lines in galaxies (Helou et al. 2000).
- [OI] is optically thick in PDRs. (Self) absorption. Vastel et al. 2002, Goicoechea et al. 2004.

C and CO line cooling





Schneider et al. 2003, S106 CO(7-6) – [CI] fine structure lines



C and CO line cooling

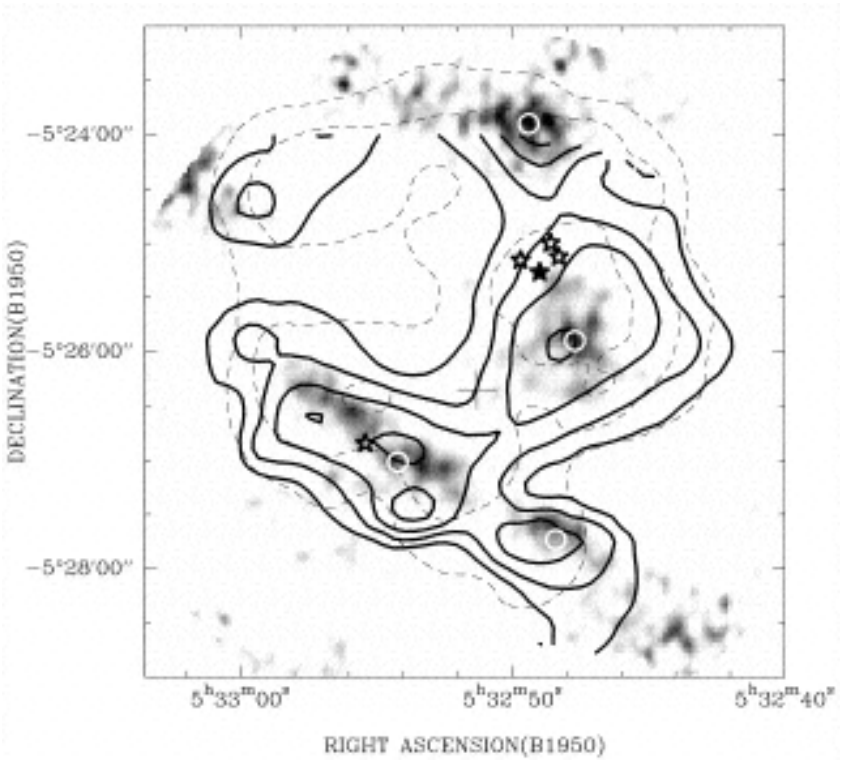
Orion Bar in CO(7-6), Wilson et al.)

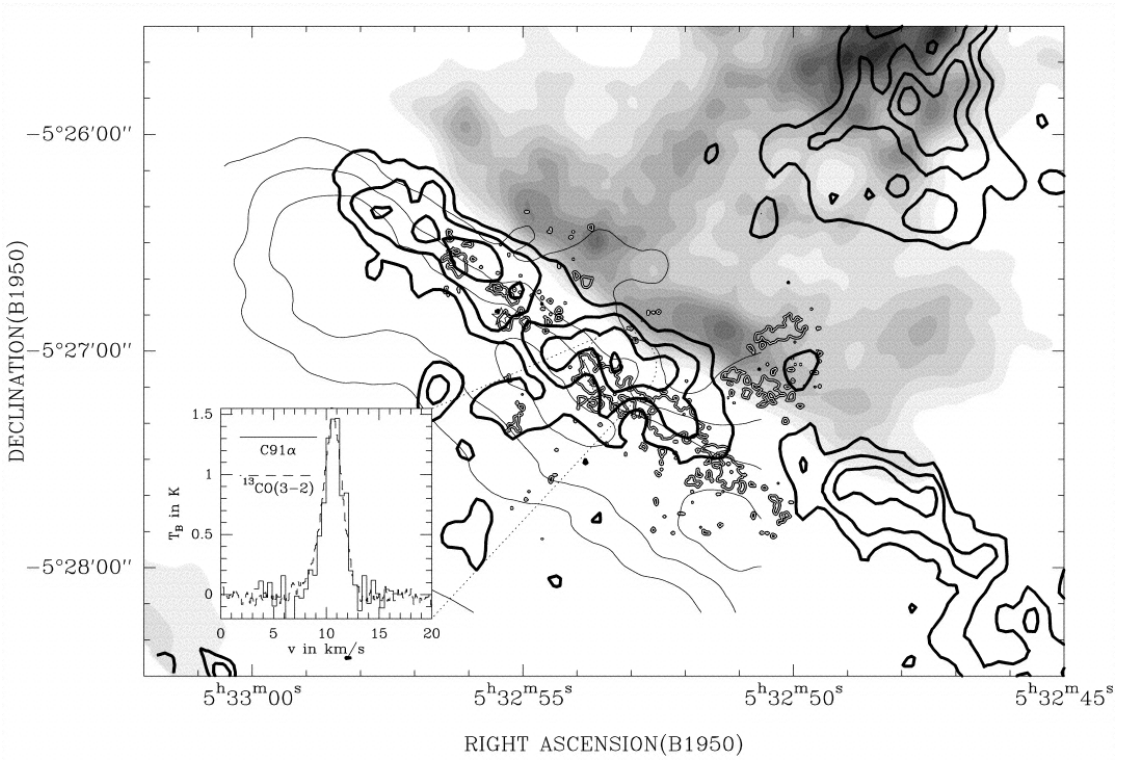
- Bright CO lines in PDRs , CO(6-5), CO(7-6) from ground based observations.
- CO line cooling is dominant over C cooling in most cases (eg, S106, High latitude cloud Bensch et al. 2003)
- C $^3P_1 - ^3P_0$ is very extended. It traces the moderately dense gas, avoids the densest regions (eg Bensch et al. 2003 SWAS, Kamegai et al. 2003 and other Mt Fuji maps)

- Spatial correlation between C and ^{13} CO; C and ^{12}CO in diffuse gas (HLC)

- CO lines are broad, while C lines can be narrow (km/s); line width close to thermal line width at 100 K, feeding of turbulence (Wyrowski et al.) ?

The radio view : recombination lines





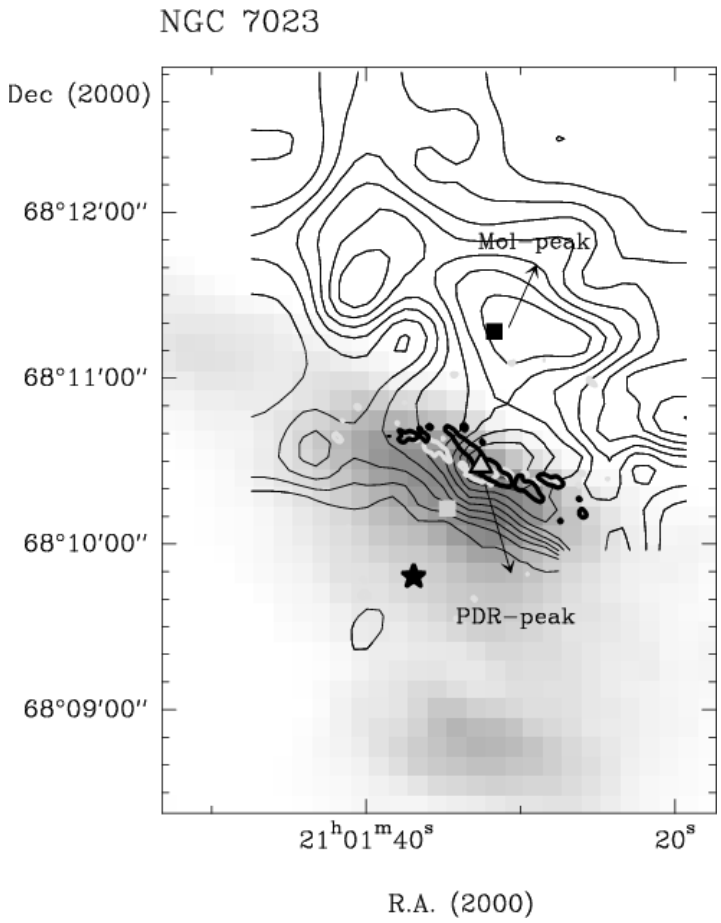
Wyrowski et al. 1997 carbon recombination lines in the Orion Bar and radio continuum emission

C recombination lines probe the region where ionised carbon recombines into C or CO.

Lines more sensitive to the electron density than [CII].

Line width gives upper limit to the kinetic temperature

Chemistry, the molecular inventory of PDRs



Fuente et al. 2003, NGC7023 HI (grey scale) HCO^+ filaments and the surrounding molecular cloud

Searching for molecules

- Where to search ?

Extended sources. Need for high resolution images (visible, near IR, millimeter lines with Interferometers + a priori information (models)

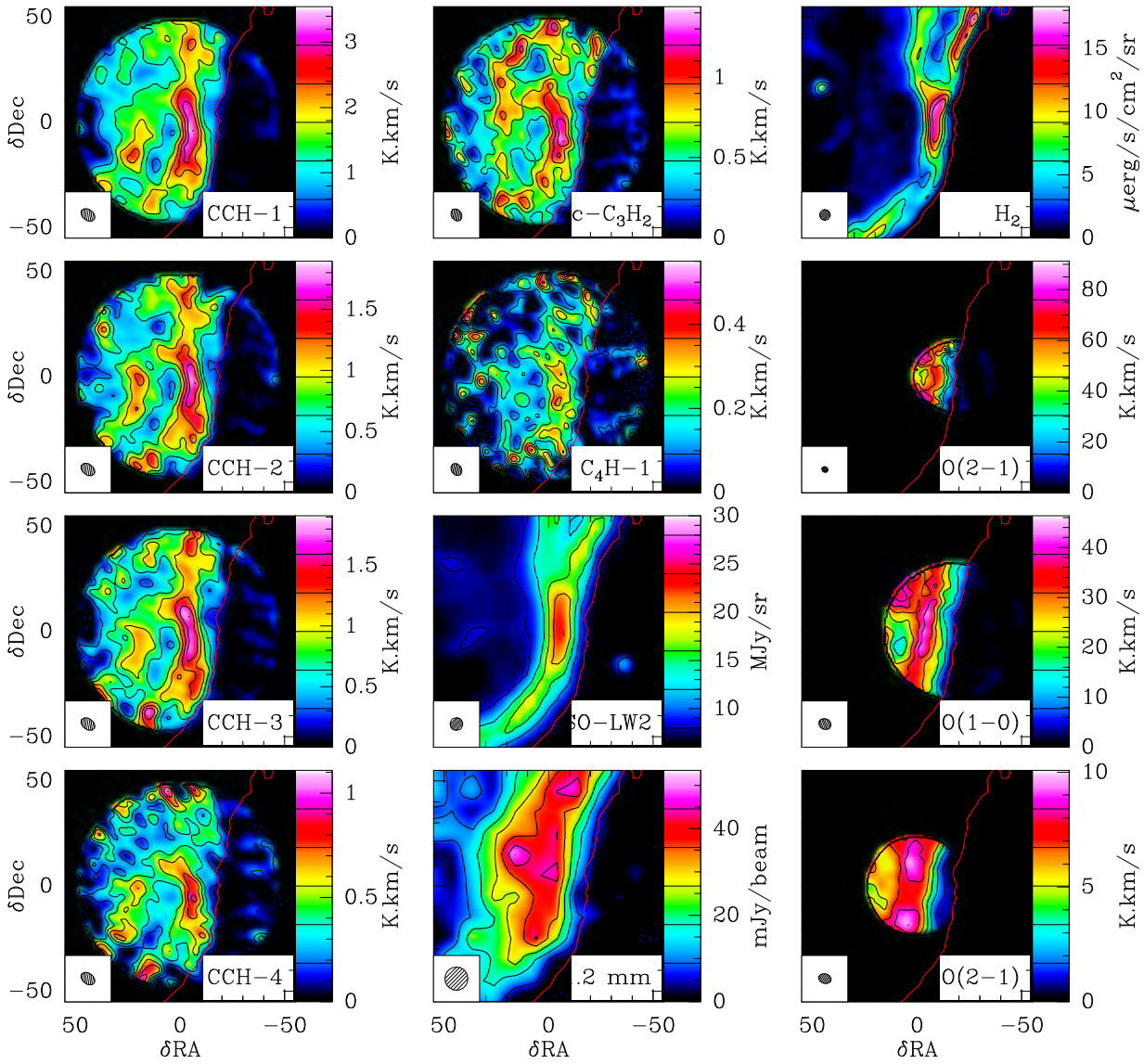
- What to search ?

Stable interstellar molecules (CO, CS, ...)

Radicals, HCO, CN, C_3, ...,

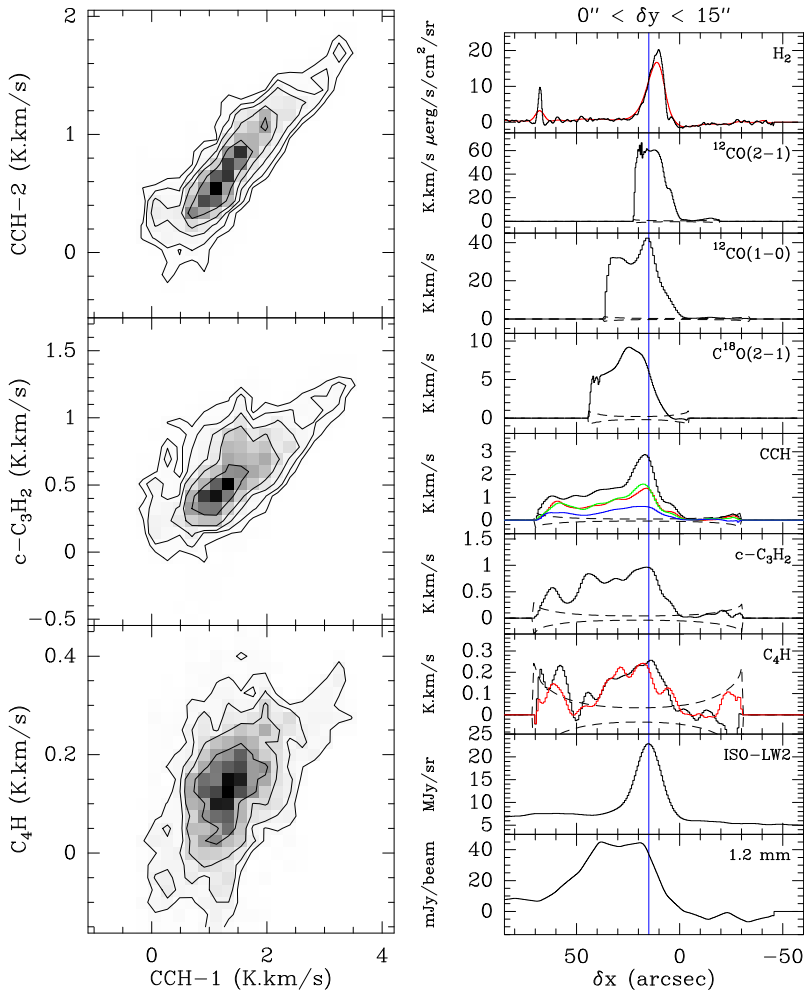
Reactive ions , CO^+)

Radicals : Carbon chains and rings



Pety et al. 2004, the edge of the horsehead nebula, viewed with the IRAM PDB interferometer + ISO and H_2 data

Carbon chains and rings in the horsehead nebula

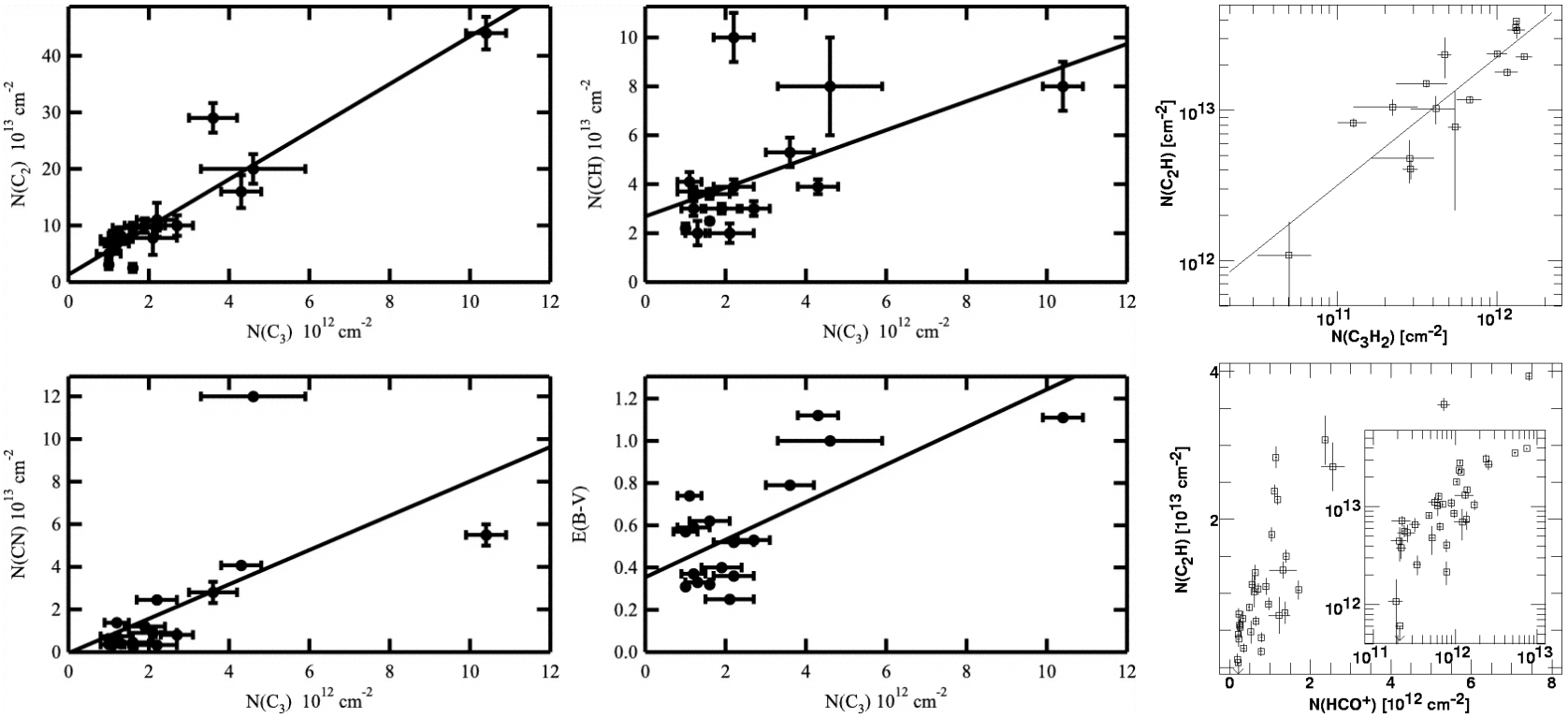


Very good correlation between CCH and c-C_3H_2, CCH and C_4H

$C^{18}O$ is found behind the PDR edge , as predicted

The Carbon chains and cycles are coincident with the PAH emission.

Back to the diffuse medium

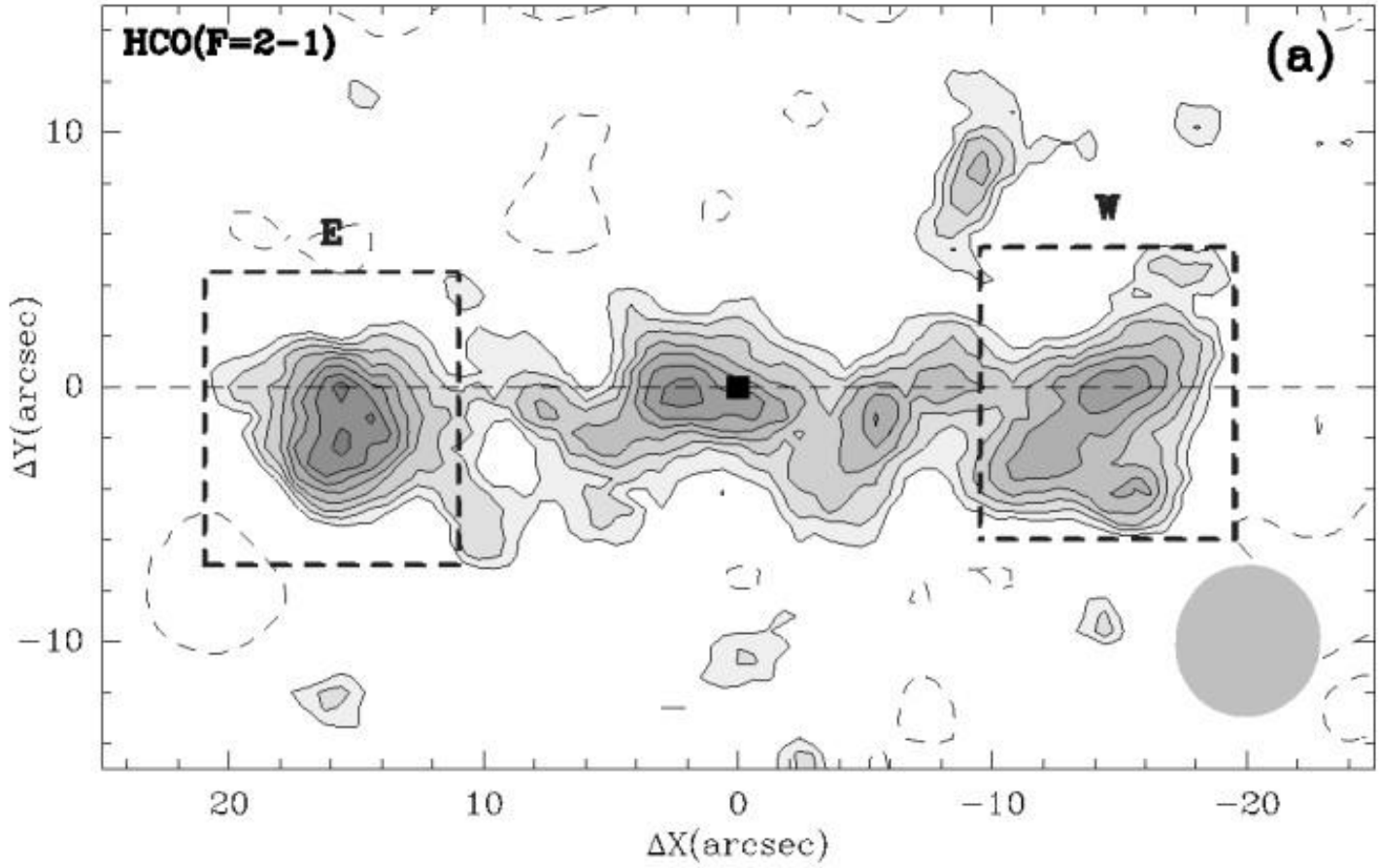


Oka et al. 2003, Lucas & Liszt 2000

Similar correlations from source to source in the diffuse ISM, C_2 and C_3 ; c-C_3H_2 and CCH

ISO detection of C_3 and C_4 in absorption (Cernicharo, Goicoechea et al.)

Other Radicals : CN, HCO



HCO in M 82, a giant PDR ? Garcia-Burillo et al. 2002

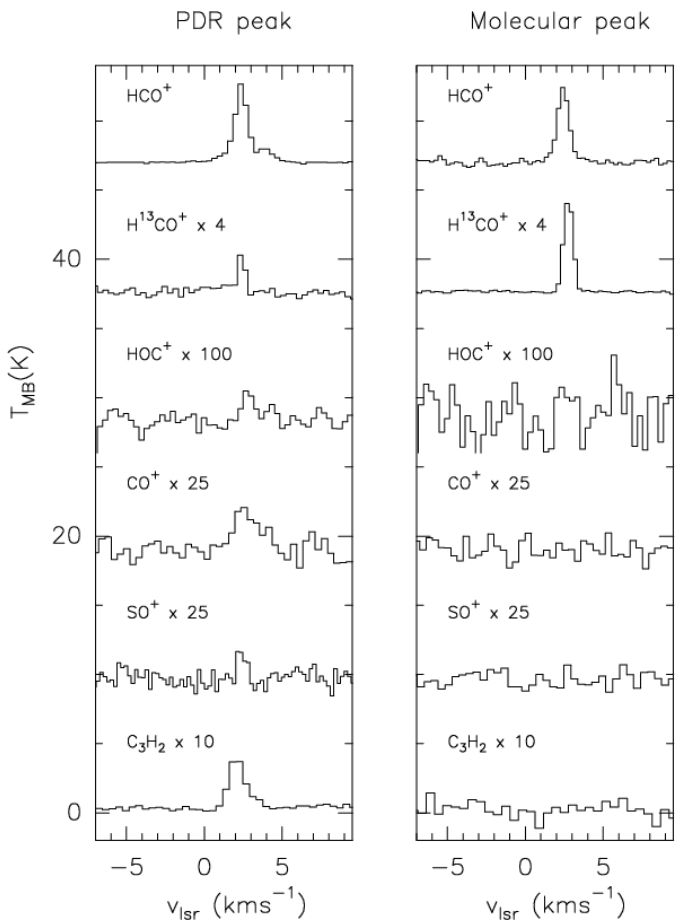
Many radicals are abundant in PDRs : CN, HCO , CCH

⇒ Tracers of PDRS

⇒ Probes of physical conditions , density, B field ?

⇒ Relation with stable molecules and probes of photodissociation processes : HCO - H_2CO CH_3OH ? ; CN, HCN HNC ; H_2O and OH ; etc.

Reactive ions



NGC 7023, Fuente et al. 2003

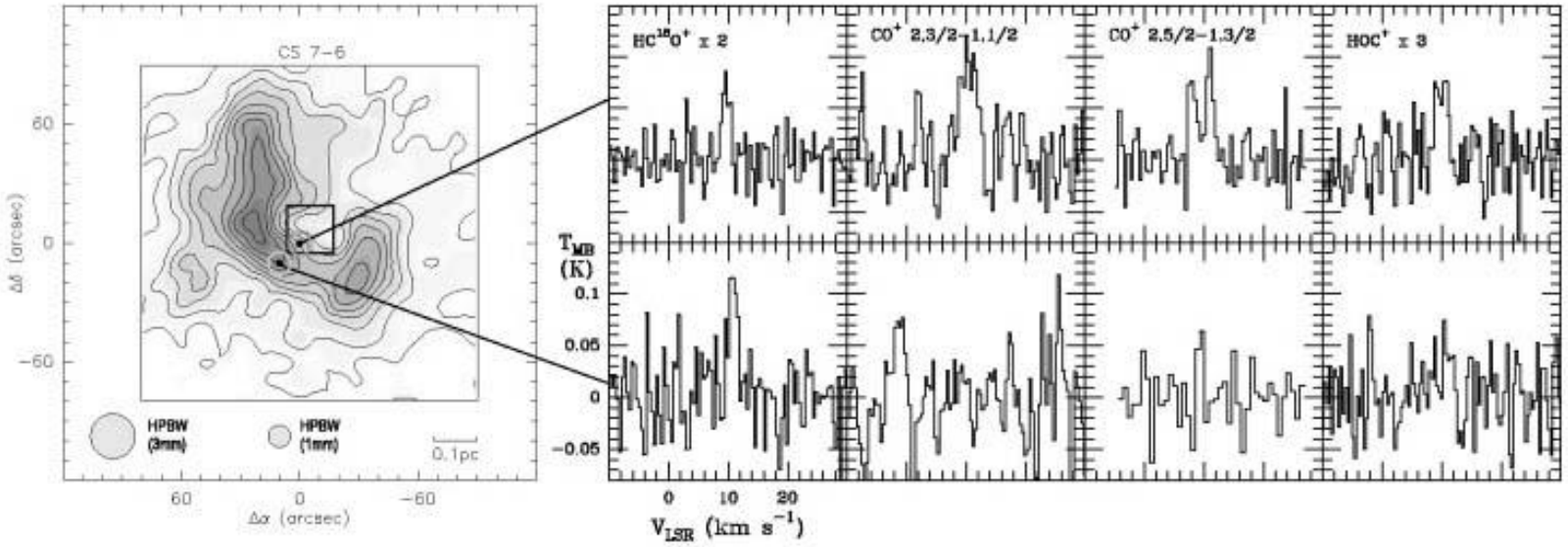
Reactive ions are destroyed rapidly by H_2

Detection in PDRs only, in the outer layers irradiated by FUV radiations

Abundance much larger than predicted by models

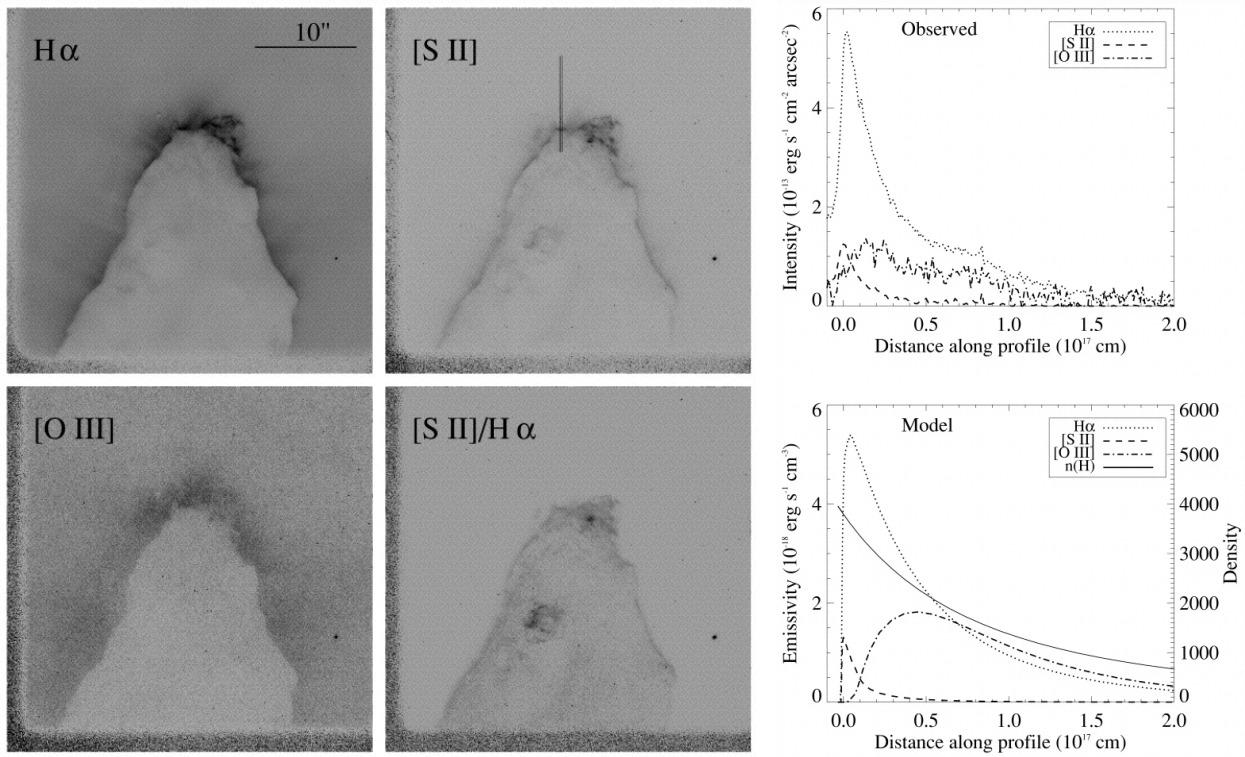
Wide lines : velocity gradients ?

Compact PDR close to HII regions



Rizzo et al. 2003, UCHII region, Mon R2

Observational evidence for photo evaporation flows



Sankrit & Hester, M 16

- Line profiles (CO^+)
- H_2 v=1-0 S(1) spatial structure (Lemaire et al., Habart et al., ...). Resolved emission ($\sim 1-2arcsec$)
- Velocity gradient from H to H_2 to C^+ to C (Lemaire et al. 99, NGC 7023).
- Molecular abundances (Ice evaporation) ? To be checked.

Future prospects

- going to large scale : extragalactic PDRs
  [CII], [CI], [OI] fine structure lines, high J CO lines, HCO in M82 (Garcia-Burilo et al. 2002)

- going to small scales : circumstellar disks, proplyds , clumps in planetary nebulae (Helix)

- Expanding the **resolution** : spatial (mm interferometer) and spectral (near IR integral field spectroscopy)

- Refining the understanding of the source structure and geometry
  plane parallel , spherical , clumpy ? inclination to the line of sight ?
  Density gradients (photoevaporation flows)
  Multiphase structure (diffuse ISM)

- Expanding the molecular inventory , eg molecules evaporated from the ice mantles ? complex organics ? more radicals ? more ions ?

- Studying the B field, Polarisation of the dust emission + Zeeman line splitting (eg M17 Brogan & Troland 2001, HI).