FUSE results concerning the diffuse and translucent clouds

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Outline

I – Diffuse and transluscent clouds

a) Generalities
b) The Meudon PDR code

II – Results of the FUSE survey

a) H_2 and HD in our Galaxy
b) H_2 and HD in the Magellanic Clouds

III - Physical and chemical properties of diffuse clouds

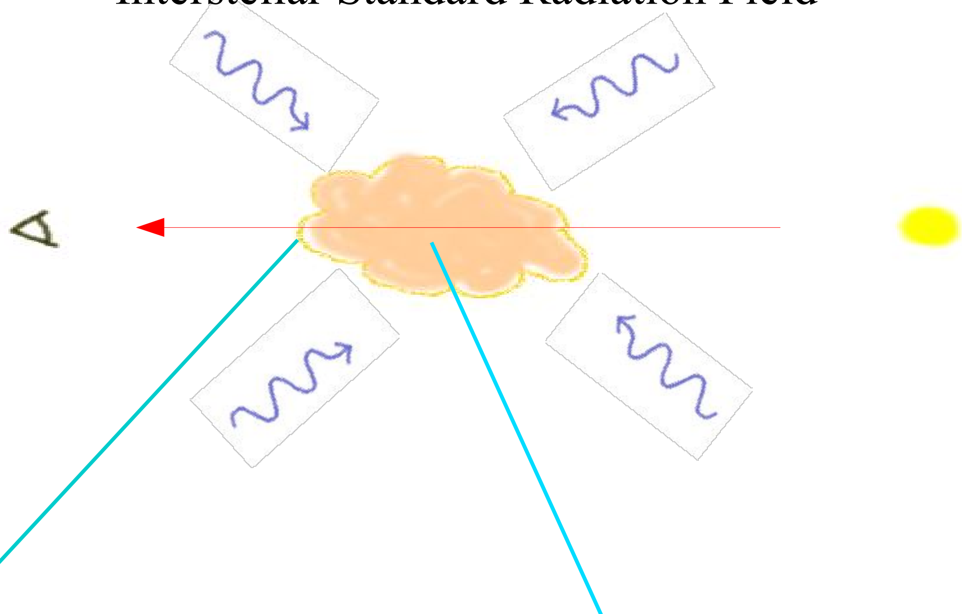
a) structure of diffuse interstellar clouds
b) the problem of the ionization
c) an open question : the excitation of H_2

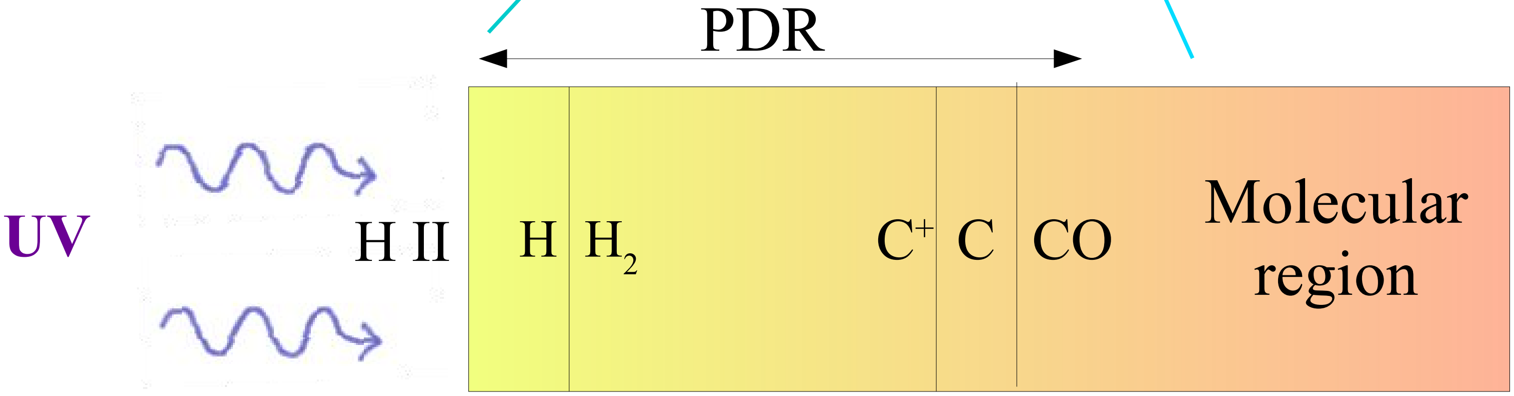
Part I : Diffuse and translucent clouds

- $n_H \sim 100\ cm^{-3}$
- embedded in the interstellar standard radiation field (ISRF)

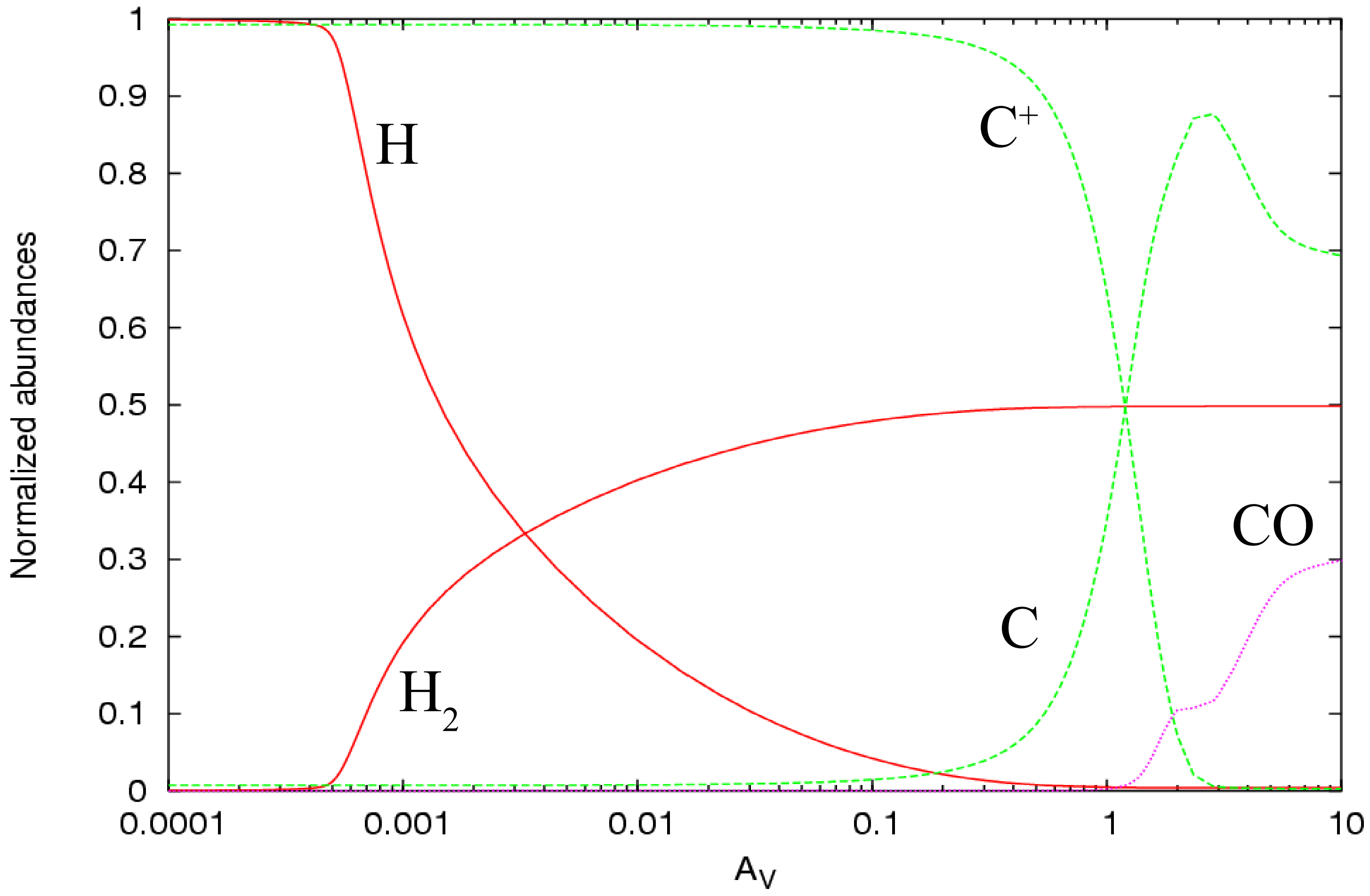
Transition between atomic and molecular form

ISRF
Interstellar Standard Radiation Field





Result from a model with : $n_H = 500$ cm^{-3}, ISRF



Observations of diffuse clouds

Partially transparent → observations in absorption possible

↓

direct determination of abundances

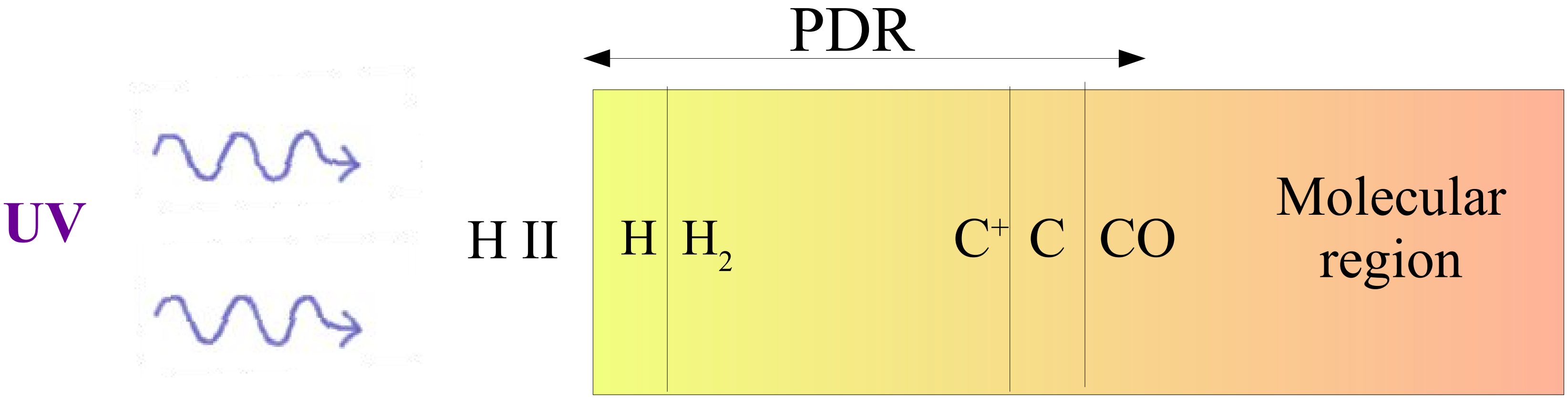
- Far UV : electronic transitions of H_2
  but also H, D, HD, CO, C I, N_2 etc ...
- Visible : OH, CH, CH^+, CN, C_2, C_3, ...
- IR : H_3^+
- Radio : HCO^+, HOC^+, NH_3, HCN, HNC, H_2S, ...

Interest :

- more simple chemistry than in dense clouds
- it is possible to study more in detail the physical processes
  - chemistry & interaction dust-gas
  - interaction matter-radiation : H_2, HD, CO
  - effect of the cosmic rays : OH, HD, H_3^+, HCO^+, HOC^+
  - effect of the magnetic field : CH^+

Modelisation : PDR code of the Observatory of Meudon

J. Le Bourlot, E. Roueff, F. Le Petit



PDR

UV

H II

H H_2

C^+ C CO

Molecular region

Stationnary model solving :

- Radiative transfer : absorption in the lines (30 000 lines for H_2)
  absorption in the continuum

- Chemistry : more than 100 chemical species
  network of more than 1000 chemical reactions

- Statistical equilibrium of the populations in the levels of H_2, HD, CO, HCO^+, CS, ...
  takes into account : radiative and collisional excitation / de-excitation
  photodissociation

- Thermal balance : heating by photoelectric effect, chemistry, cosmic rays
  cooling in the lines of the atoms and molecules

Can be used to study PDR and dense clouds

Downloadable at http://aristote.obspm.fr/MIS/

Requires : fortran 90
libraries BLAS and LAPACK

Parameters :

- density (constant or density profile)
- incident radiation field (scale the ISRF or a black body)
- abundances of elements
- other specific parameters :
  - extinction curve
  - flux of cosmic rays
  - Doppler parameter
  - ...

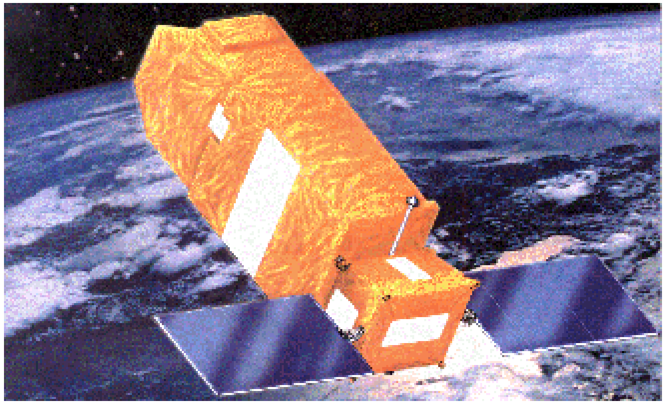
Results :

- abundances of atoms and molecules at each point
- column densities
- excitation of some species
- intensities
- rate of heating and cooling processes
- temperature profile
- possible analysis of the chemistry
- ....

Part II : The FUSE Survey - (Far Ultraviolet Spectroscopic Explorer)

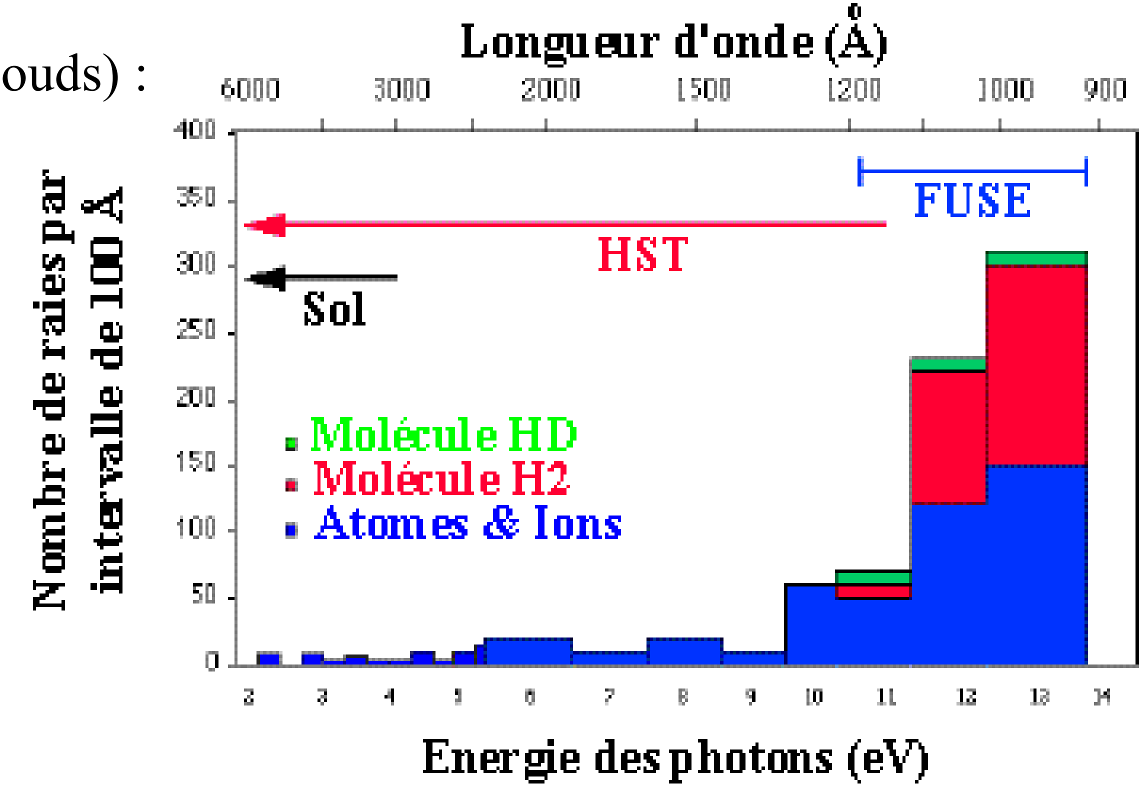
USA – Canada – France (FUSE french team - A. Vidal-Madjar, R. Ferlet)

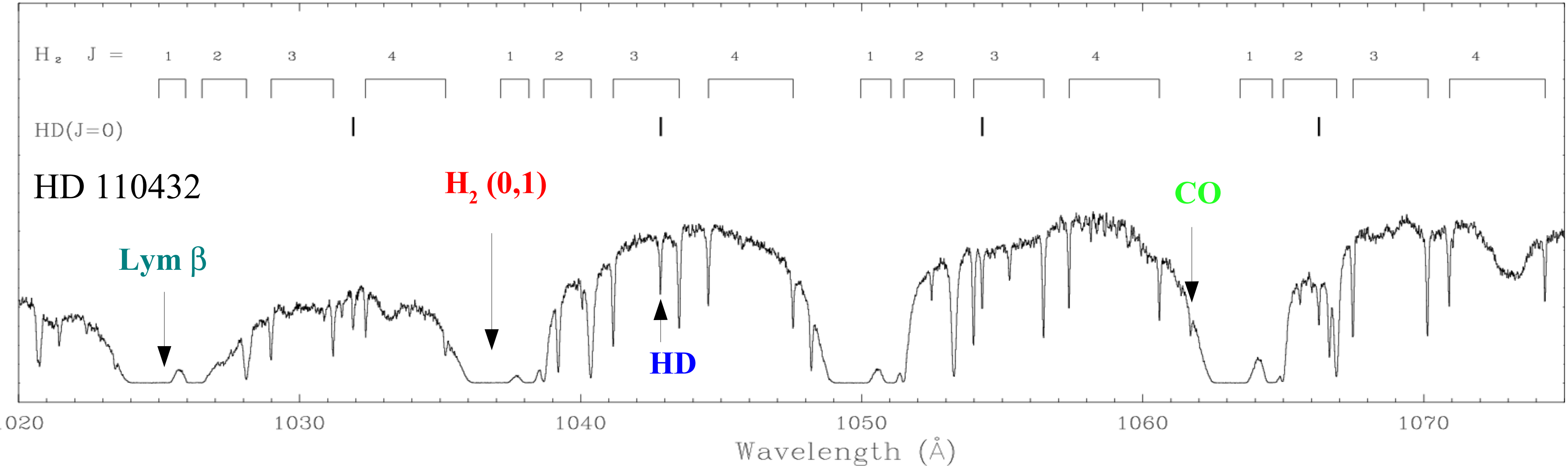
Launched in **1999**
Resolution : ~20 000 (~ 0.05 Å, ~ 15 km s^{-1})
wavelengths : **905 – 1187 Å**
H_2, HD, D, CO, C I, ...

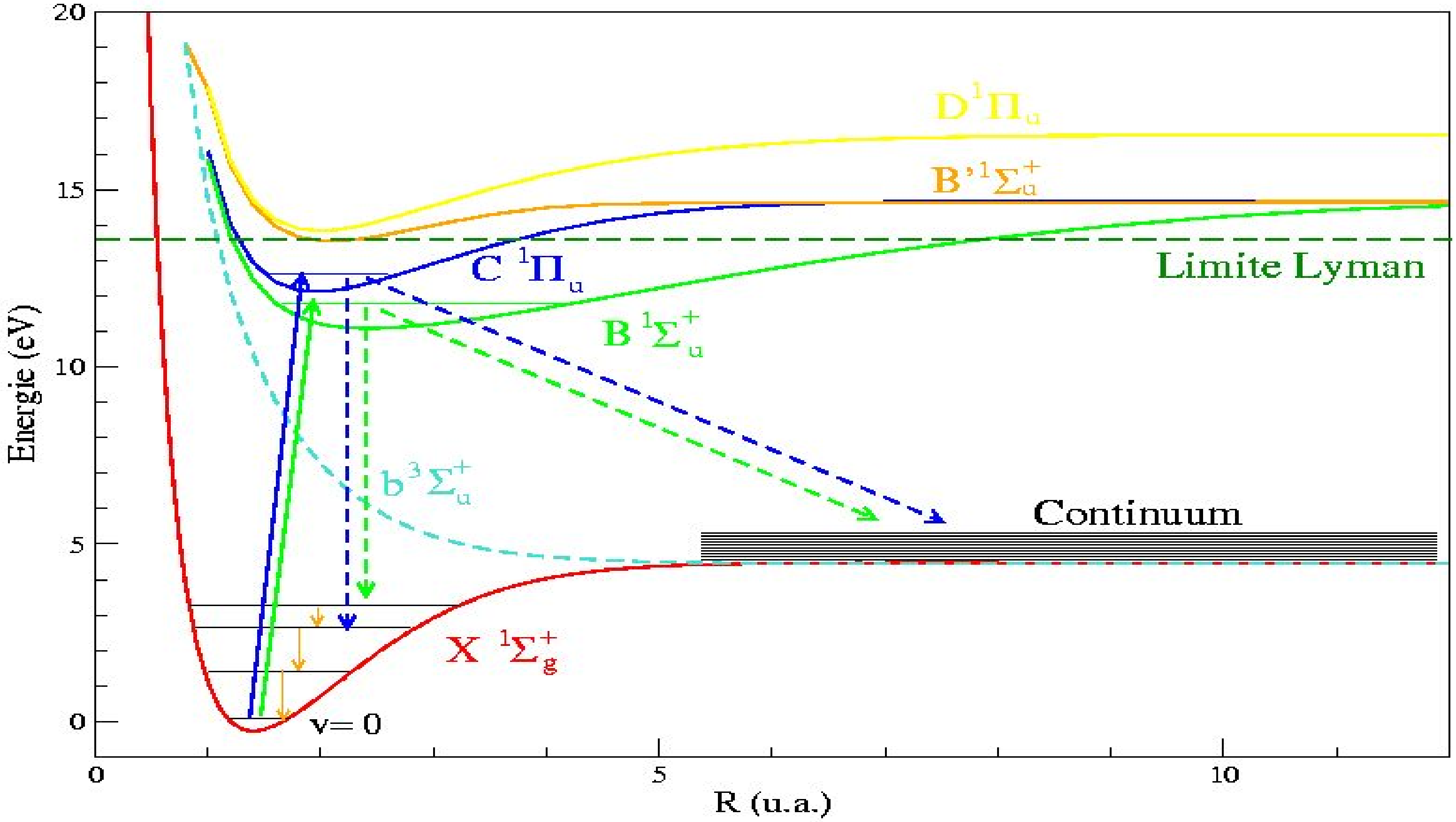


Missions (for diffuse and transluscent clouds) :

1 – Determination of abundances
2 – D/H
3 – Excitation of H_2 --- T_{kin}
4 – ratios CO/H_2
5 – physical conditions




H_2 J =
1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
HD(J=0)
HD 110432
H_2 (0,1)
Lym β
HD
CO
020
1030
1040
1050
1060
1070
Wavelength (Å)


$D^1\Pi_u$
$B'^1\Sigma_u^+$
$C\ ^1\Pi_u$
Limite Lyman
$B\ ^1\Sigma_u^+$
$b^3\Sigma_u^+$
Continuum
$X\ ^1\Sigma_g^+$
v= 0
Energie (eV)
20
15
10
5
0
0
5
10
R (u.a.)

H_2 survey in our Galaxy

(Rachford et al. 2002)

Observations : Analysis of 23 lines of sight
higher E(B-V) than Copernicus => higher N(H_2)

Analysis : H_2 in J = 0 and 1, T_{01}

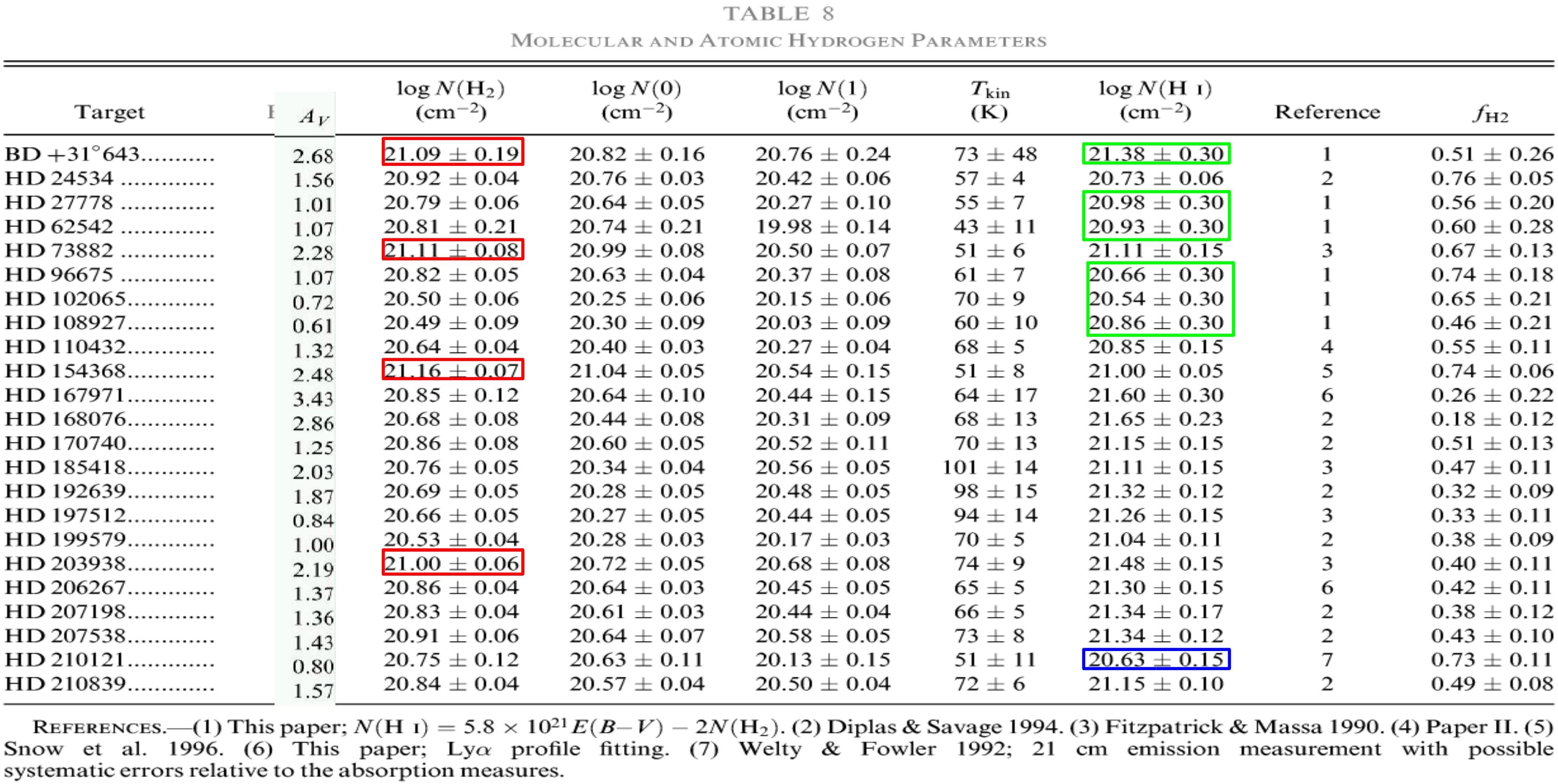


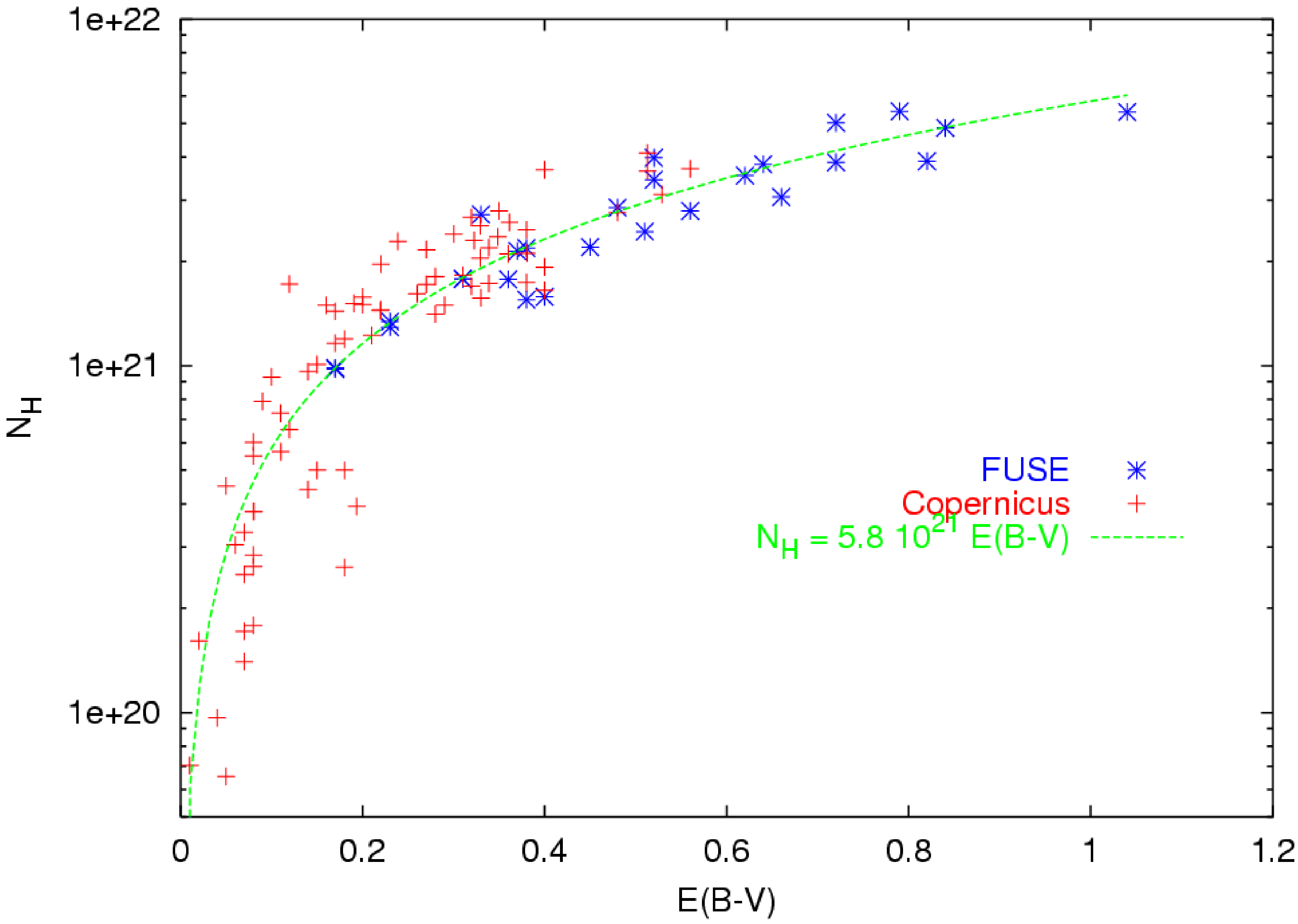
TABLE 8

MOLECULAR AND ATOMIC HYDROGEN PARAMETERS

Target	A_V	log $N(H_2)$ (cm^{-2})	log $N(0)$ (cm^{-2})	log $N(1)$ (cm^{-2})	T_{kin} (K)	log N(H I) (cm^{-2})	Reference	f_{H2}
BD +31°643..........	2.68	21.09 ± 0.19	20.82 ± 0.16	20.76 ± 0.24	73 ± 48	21.38 ± 0.30	1	0.51 ± 0.26
HD 24534	1.56	20.92 ± 0.04	20.76 ± 0.03	20.42 ± 0.06	57 ± 4	20.73 ± 0.06	2	0.76 ± 0.05
HD 27778	1.01	20.79 ± 0.06	20.64 ± 0.05	20.27 ± 0.10	55 ± 7	20.98 ± 0.30	1	0.56 ± 0.20
HD 62542	1.07	20.81 ± 0.21	20.74 ± 0.21	19.98 ± 0.14	43 ± 11	20.93 ± 0.30	1	0.60 ± 0.28
HD 73882	2.28	21.11 ± 0.08	20.99 ± 0.08	20.50 ± 0.07	51 ± 6	21.11 ± 0.15	3	0.67 ± 0.13
HD 96675	1.07	20.82 ± 0.05	20.63 ± 0.04	20.37 ± 0.08	61 ± 7	20.66 ± 0.30	1	0.74 ± 0.18
HD 102065............	0.72	20.50 ± 0.06	20.25 ± 0.06	20.15 ± 0.06	70 ± 9	20.54 ± 0.30	1	0.65 ± 0.21
HD 108927............	0.61	20.49 ± 0.09	20.30 ± 0.09	20.03 ± 0.09	60 ± 10	20.86 ± 0.30	1	0.46 ± 0.21
HD 110432............	1.32	20.64 ± 0.04	20.40 ± 0.03	20.27 ± 0.04	68 ± 5	20.85 ± 0.15	4	0.55 ± 0.11
HD 154368............	2.48	21.16 ± 0.07	21.04 ± 0.05	20.54 ± 0.15	51 ± 8	21.00 ± 0.05	5	0.74 ± 0.06
HD 167971............	3.43	20.85 ± 0.12	20.64 ± 0.10	20.44 ± 0.15	64 ± 17	21.60 ± 0.30	6	0.26 ± 0.22
HD 168076............	2.86	20.68 ± 0.08	20.44 ± 0.08	20.31 ± 0.09	68 ± 13	21.65 ± 0.23	2	0.18 ± 0.12
HD 170740............	1.25	20.86 ± 0.08	20.60 ± 0.05	20.52 ± 0.11	70 ± 13	21.15 ± 0.15	2	0.51 ± 0.13
HD 185418............	2.03	20.76 ± 0.05	20.34 ± 0.04	20.56 ± 0.05	101 ± 14	21.11 ± 0.15	3	0.47 ± 0.11
HD 192639............	1.87	20.69 ± 0.05	20.28 ± 0.05	20.48 ± 0.05	98 ± 15	21.32 ± 0.12	2	0.32 ± 0.09
HD 197512............	0.84	20.66 ± 0.05	20.27 ± 0.05	20.44 ± 0.05	94 ± 14	21.26 ± 0.15	3	0.33 ± 0.11
HD 199579............	1.00	20.53 ± 0.04	20.28 ± 0.03	20.17 ± 0.03	70 ± 5	21.04 ± 0.11	2	0.38 ± 0.09
HD 203938............	2.19	21.00 ± 0.06	20.72 ± 0.05	20.68 ± 0.08	74 ± 9	21.48 ± 0.15	3	0.40 ± 0.11
HD 206267............	1.37	20.86 ± 0.04	20.64 ± 0.03	20.45 ± 0.05	65 ± 5	21.30 ± 0.15	6	0.42 ± 0.11
HD 207198............	1.36	20.83 ± 0.04	20.61 ± 0.03	20.44 ± 0.04	66 ± 5	21.34 ± 0.17	2	0.38 ± 0.12
HD 207538............	1.43	20.91 ± 0.06	20.64 ± 0.07	20.58 ± 0.05	73 ± 8	21.34 ± 0.12	2	0.43 ± 0.10
HD 210121............	0.80	20.75 ± 0.12	20.63 ± 0.11	20.13 ± 0.15	51 ± 11	20.63 ± 0.15	7	0.73 ± 0.11
HD 210839............	1.57	20.84 ± 0.04	20.57 ± 0.04	20.50 ± 0.04	72 ± 6	21.15 ± 0.10	2	0.49 ± 0.08

REFERENCES.—(1) This paper; $N(\mathrm{H\,I}) = 5.8 \times 10^{21} E(B-V) - 2N(H_2)$. (2) Diplas & Savage 1994. (3) Fitzpatrick & Massa 1990. (4) Paper II. (5) Snow et al. 1996. (6) This paper; Lyα profile fitting. (7) Welty & Fowler 1992; 21 cm emission measurement with possible systematic errors relative to the absorption measures.

The gas – dust relationship

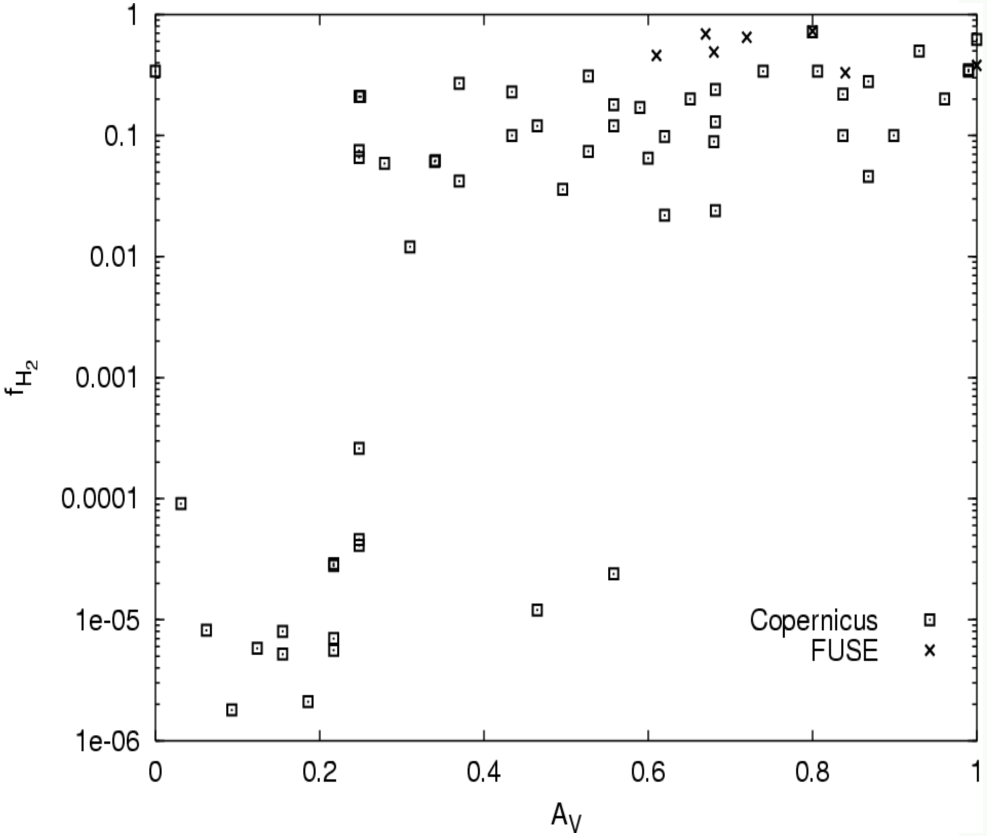


$$N_H = N(H) + 2\,N(H_2) = 5.8\times10^{21}\,E(B-V)$$

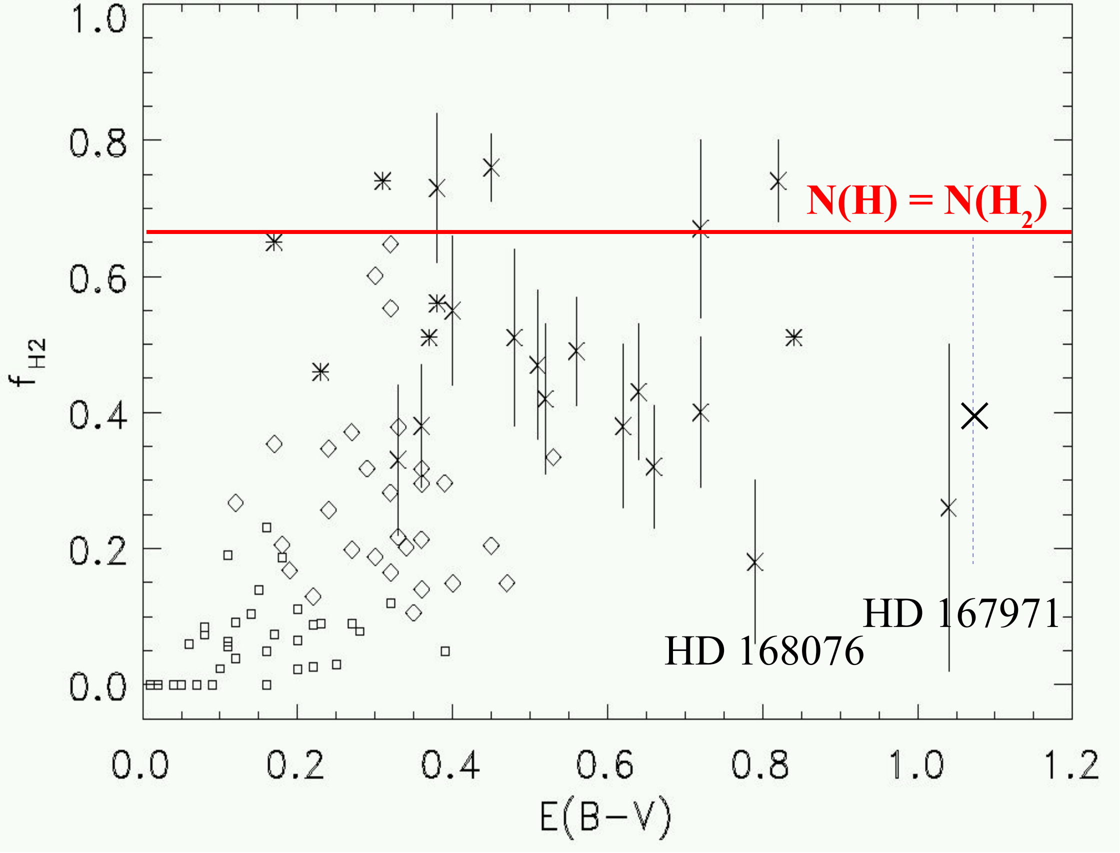
Bohlin et al. (1978)

Molecular fraction :

$$f = \frac{2N(H_2)}{[\,N(H) + 2N(H_2)\,]}$$



Rachford et al. (2002)



Try to detect **translucent clouds** : i.e. $\mathbf{A_V > 1}$

Definition from van Dishoeck and Black (1988)

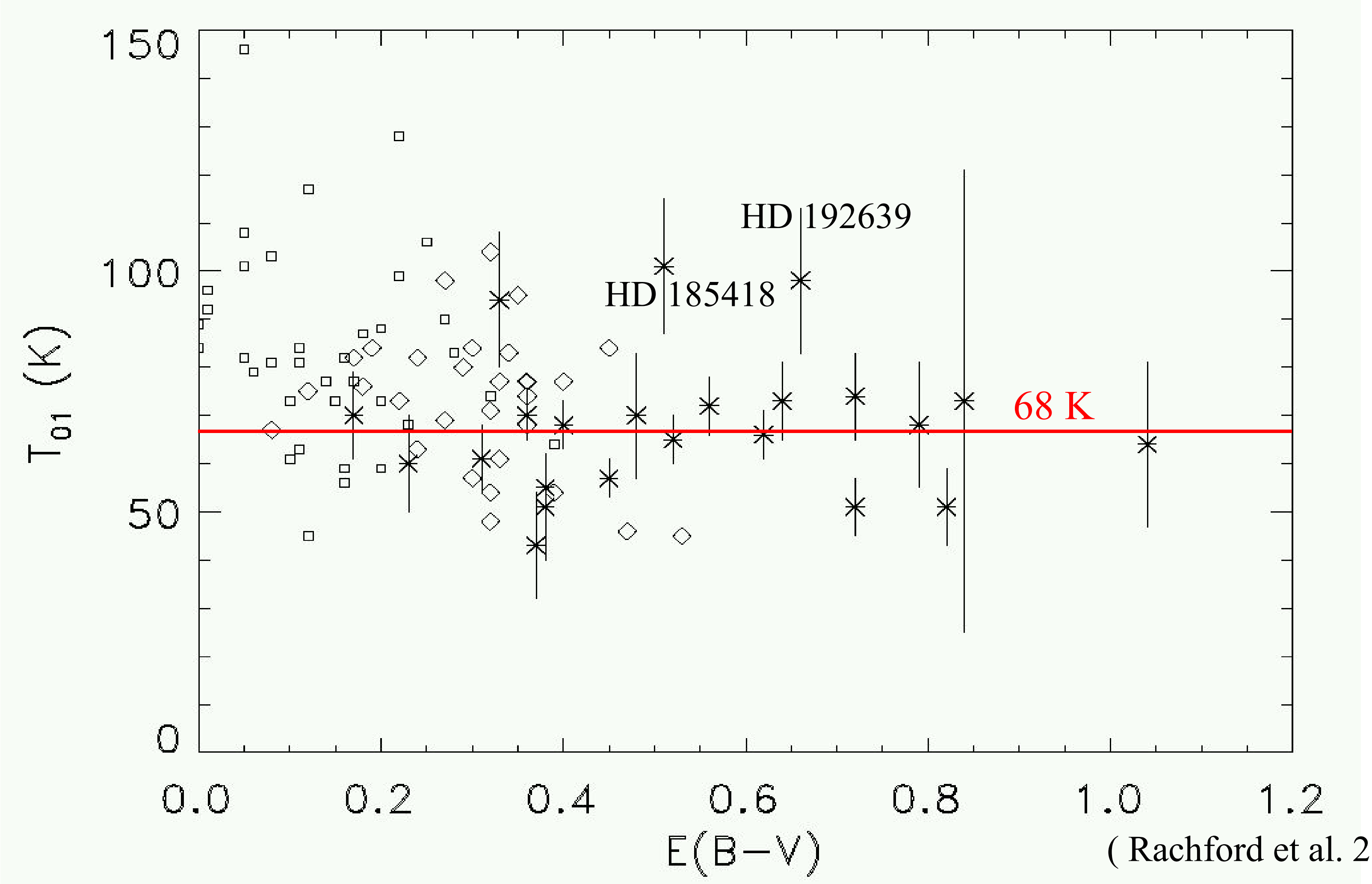
~ E(B-V) > 0.32

f > 0.9

no f > 0.8 ➔ we do not observe translucent clouds

Temperature of H_2 – J = 0, 1

$$T_{01} = -170.5 \ \ln \frac{9\,N(H_2, J=0)}{N(H_2, J=1)}$$



(Rachford et al. 2002)

Copernicus : T_{01} = 55 ± 8 K

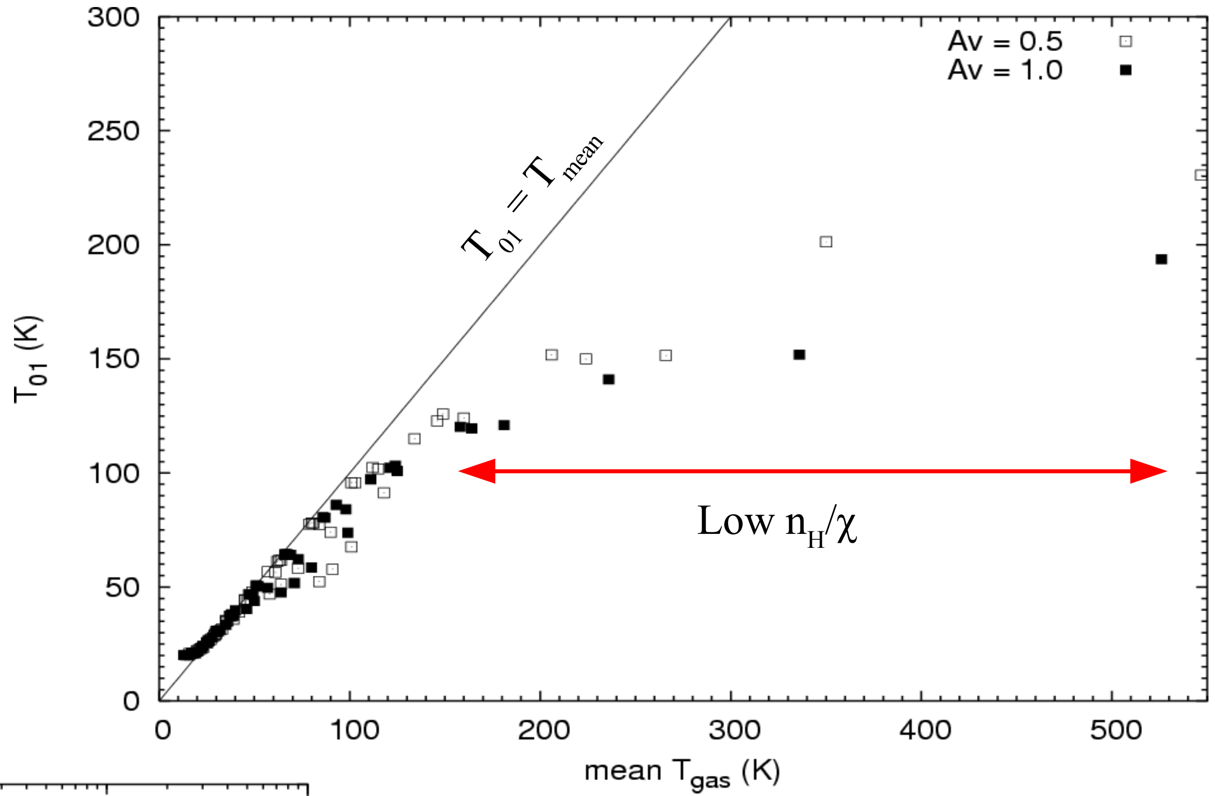
FUSE : T_{01} = 68 ± 15 K

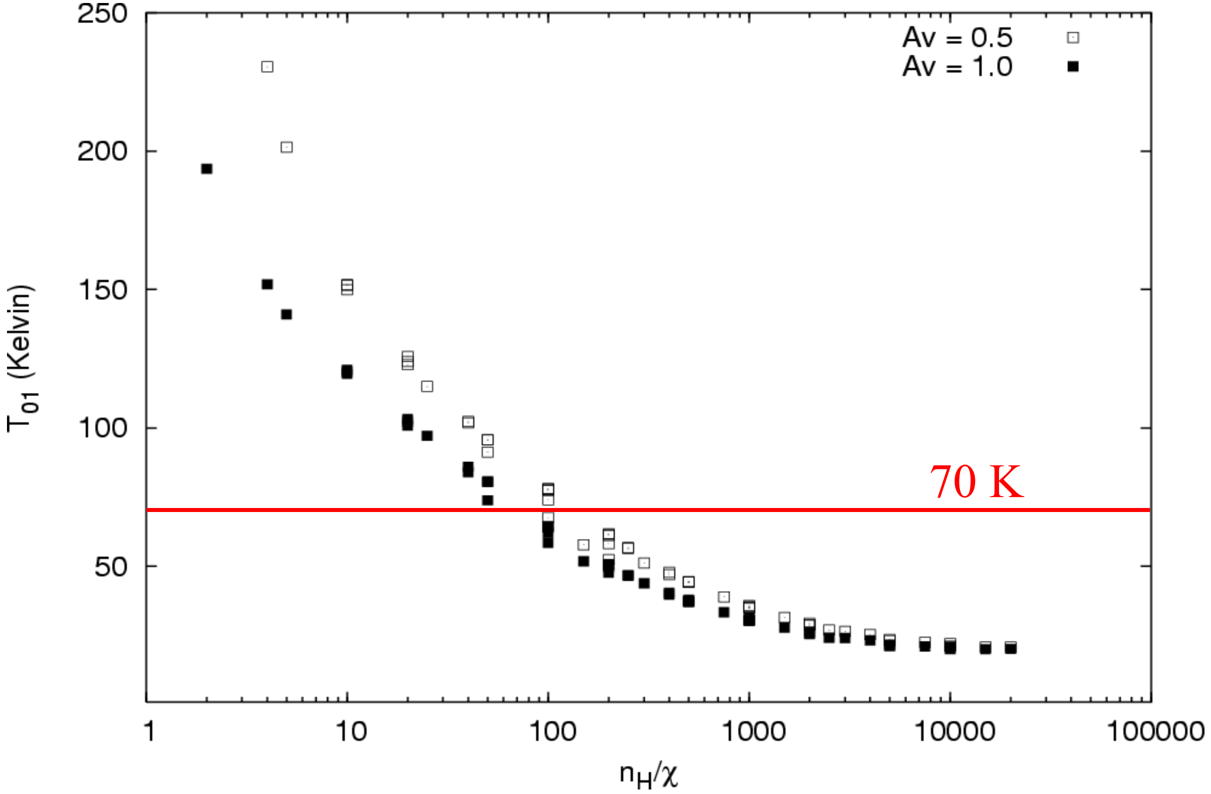
Low n_H/χ : effet of radiative pumping

$T_{01} < T_{mean}$

For all the observed T_{01}

$T_{01} \approx T_{moy}$





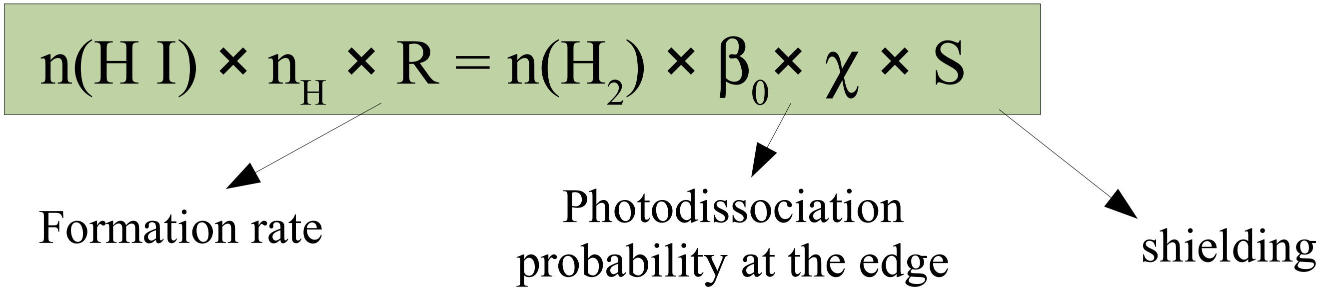
T_{01} is a good constraint on n_H/χ

models give :

$n_H/\chi \approx 100$

Formation rate of H_2

Gry et al. (2002), A&A 391, 675.



$$n(\mathrm{H\ I}) \times n_H \times R = n(H_2) \times \beta_0 \times \chi \times S$$

Formation rate

Photodissociation probability at the edge

shielding

observations towards 3 lines of sight towards the Chameleon :

	HD 102065	HD 108927	HD 96675
E(B-V)	0.17	0.23	0.31
A_V	0.67	0.68	1.1
N_H	9.9×10^{20}	1.3×10^{21}	1.8×10^{21}

chosen since $\chi = 1$

hypothesis : homogeneous medium

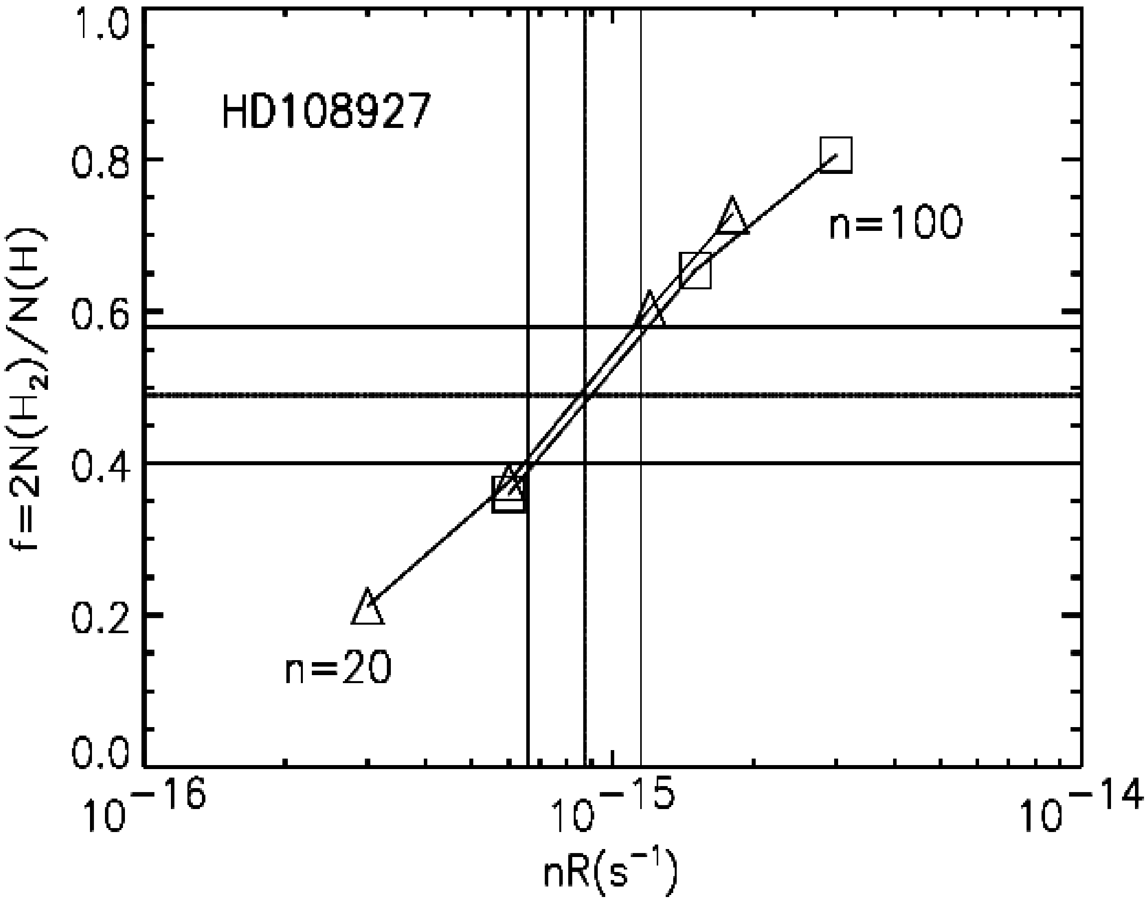
$$n_H \times R = \frac{1}{2}\,\frac{f}{1-f} \times \beta_0 \times \langle S \rangle$$

Numerical model :

$$n_H \times R = \frac{1}{2}\,\frac{f}{1-f} \times \beta_0 \times \langle S \rangle$$

n_H R : free parameter
f : observational constraint

$$\mathbf{n_H R \sim 0.87 \times 10^{-15}\ s^{-1}}$$



Hypothesis : stationarity
- direct link between the density and the temperature
- which density gives the observed T_{01} ?

$$\mathbf{\langle R \rangle \sim 4.0 \times 10^{-17}\ cm^3\ s^{-1}}$$

Copernicus : **$\langle R \rangle \sim 3.0 \times 10^{-17}$ cm^3 s^{-1}** (Jura 1975)

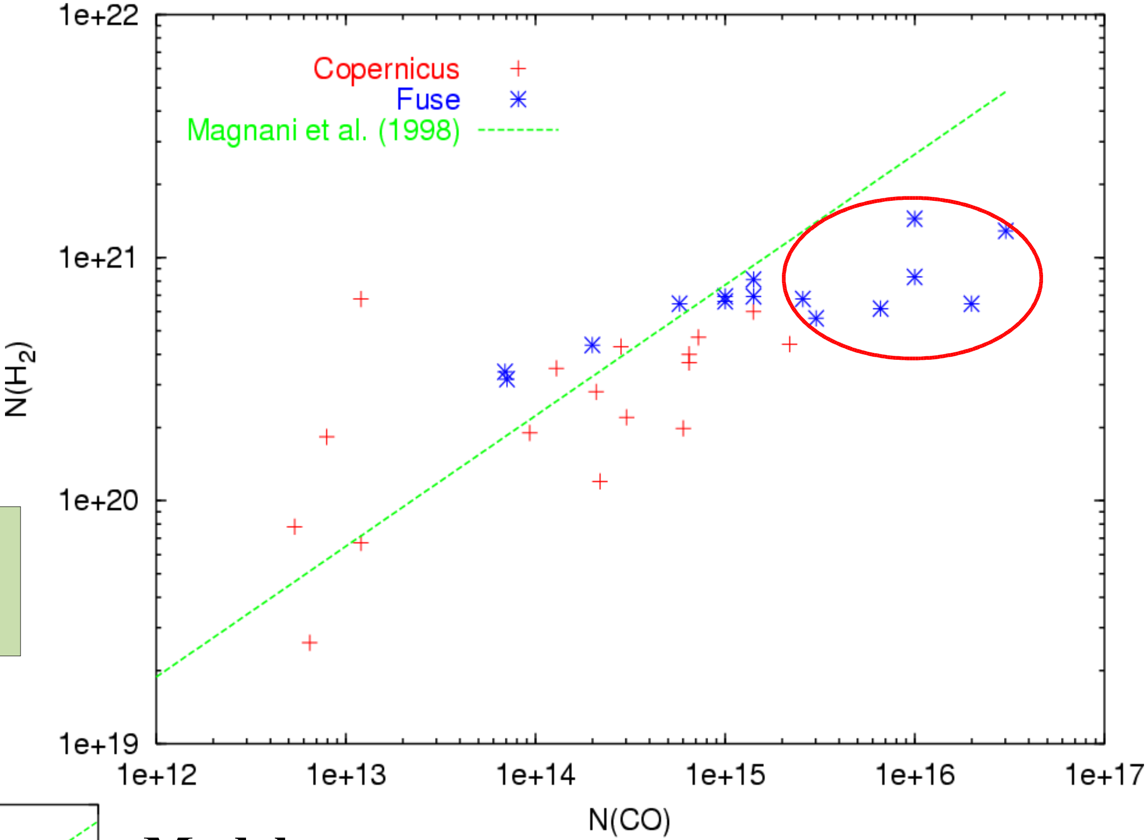
The relation $N(H_2)$ – N(CO)

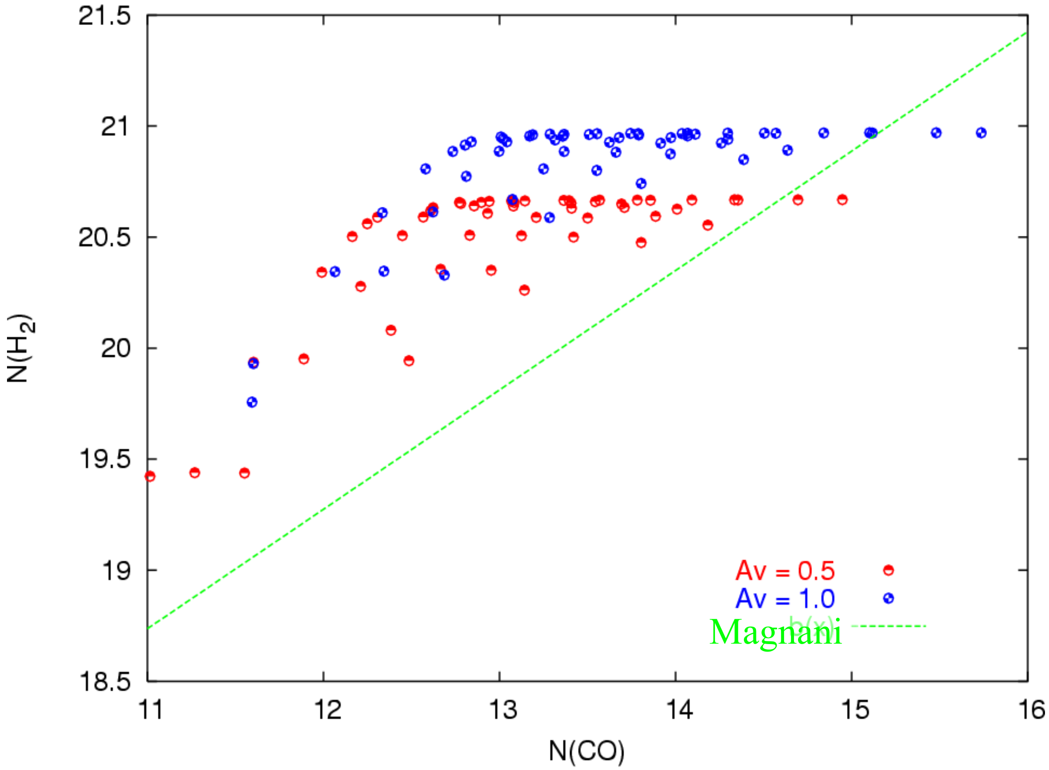
Observations

$$\log N(CO) = 1.86 \log N(H_2) - 23.85$$

Magnani et al. (1998)

FUSE observations do not follow the relationship $N(H_2)$ – N(CO)





Models

Some problems with models :

- shielding : clumps ?

Sensitivity of CO to photodissociation

But also detections of HCO^+ (Liszt & Lucas)

$$HCO^+ + e^- \longrightarrow CO + H$$

Problems with the formation rate of HCO^+

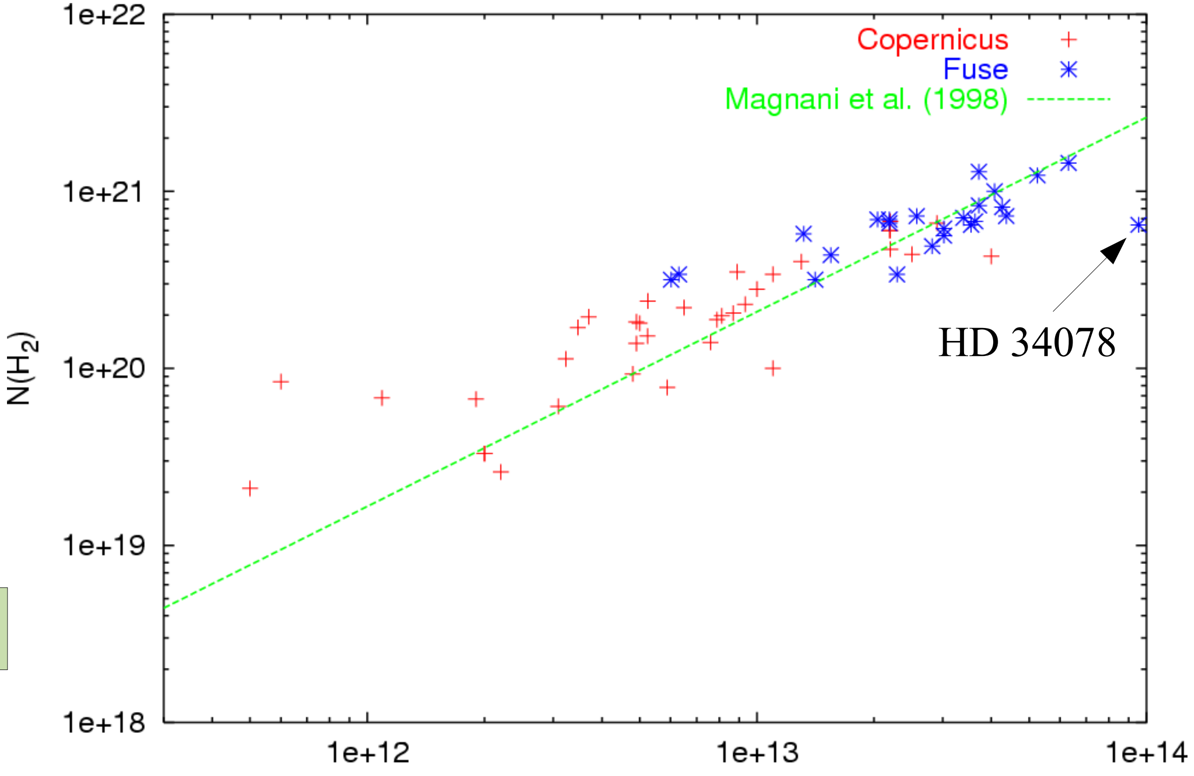
Relation $N(H_2)$ – N(CH)

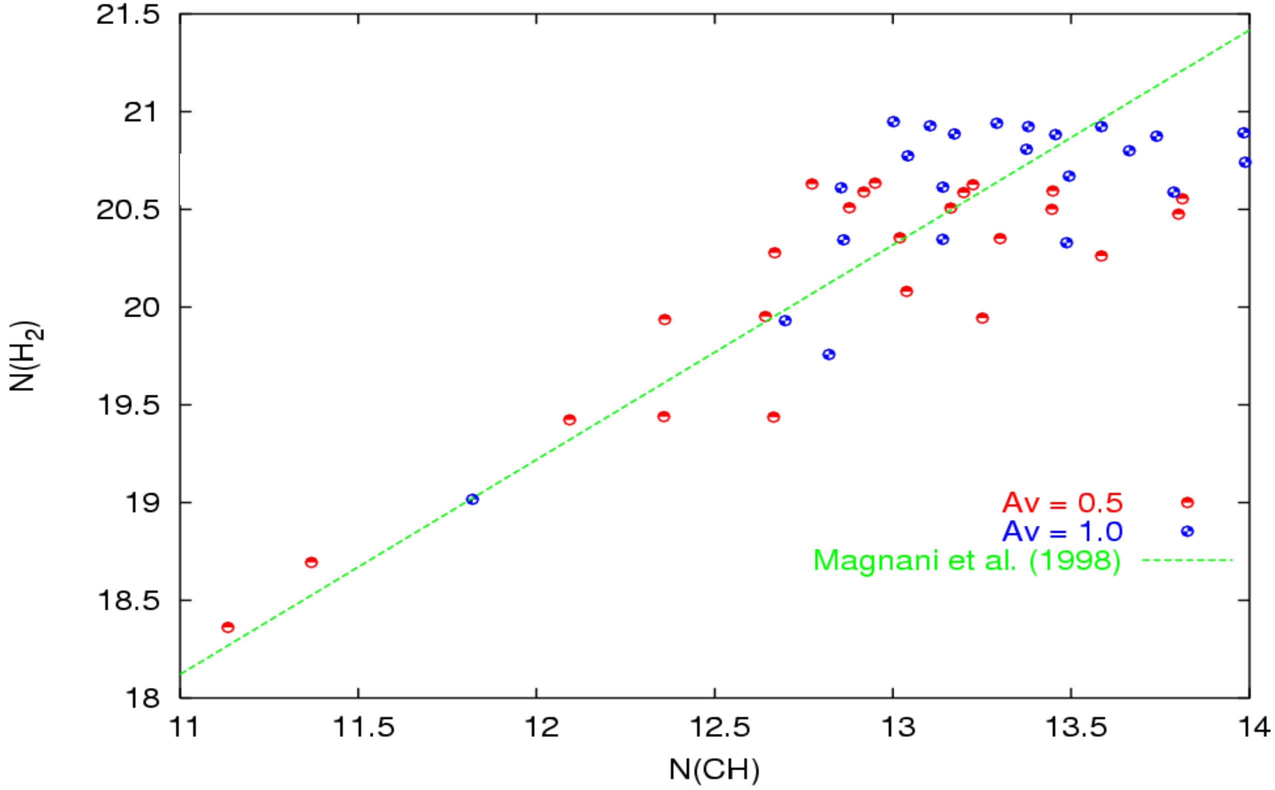
Observations

$$\log N(CH) = 0.91 \log N(H_2) - 5.49$$

Magnani et al. (1998)

Very good relationship $N(H_2)$ - N(CH)





Models

Good agreement

HD survey in our Galaxy

French FUSE team – Lacour et al. (A&A, 2005)

Why study HD:

① **determination of the ratio D/H** : one of the main objectives of the FUSE mission

② simple molecule : **good test for models**

③ **constraint on the flux of cosmic rays**

Physics of HD

- Destruction process : **photodissociation**

same electronic structure as H_2

same probability of photodissociation at the edge of the clouds

- Formation process : **formation in gas phase**

$$\mathrm{H} + \text{cosmic ray} \longrightarrow \mathrm{H}^+ + e^-$$

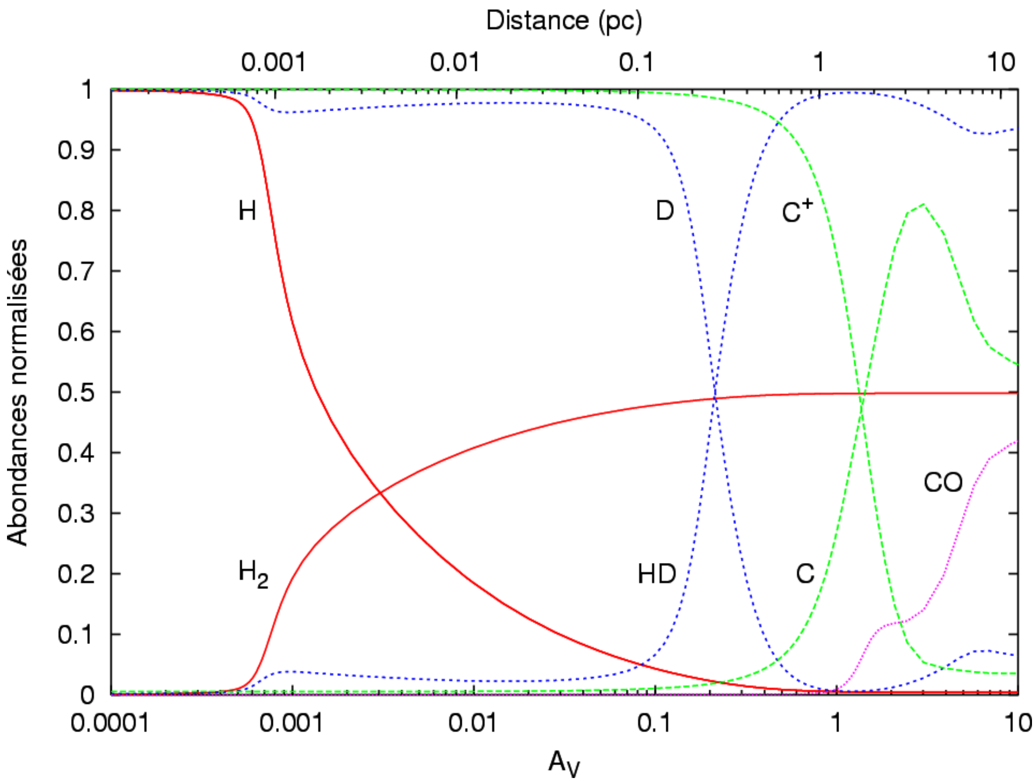
$$\mathrm{H}^+ + \mathrm{D} \longrightarrow \mathrm{D}^+ + \mathrm{H}$$

$$\mathrm{H}_2 + \mathrm{D}^+ \longrightarrow \mathrm{HD} + \mathrm{H}^+$$

Models :

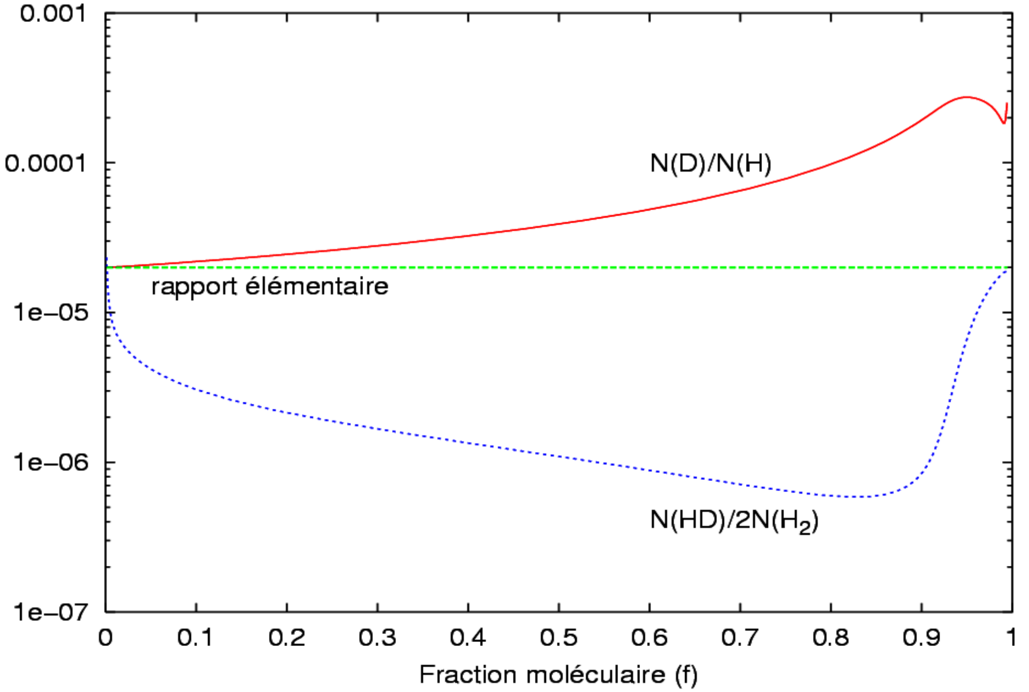
$n_H = 500$ cm^{-3}, $\chi = 1$, D/H = 2×10^{-5}

Because HD is less abundant than H_2 its formation occurs deeper in the clouds



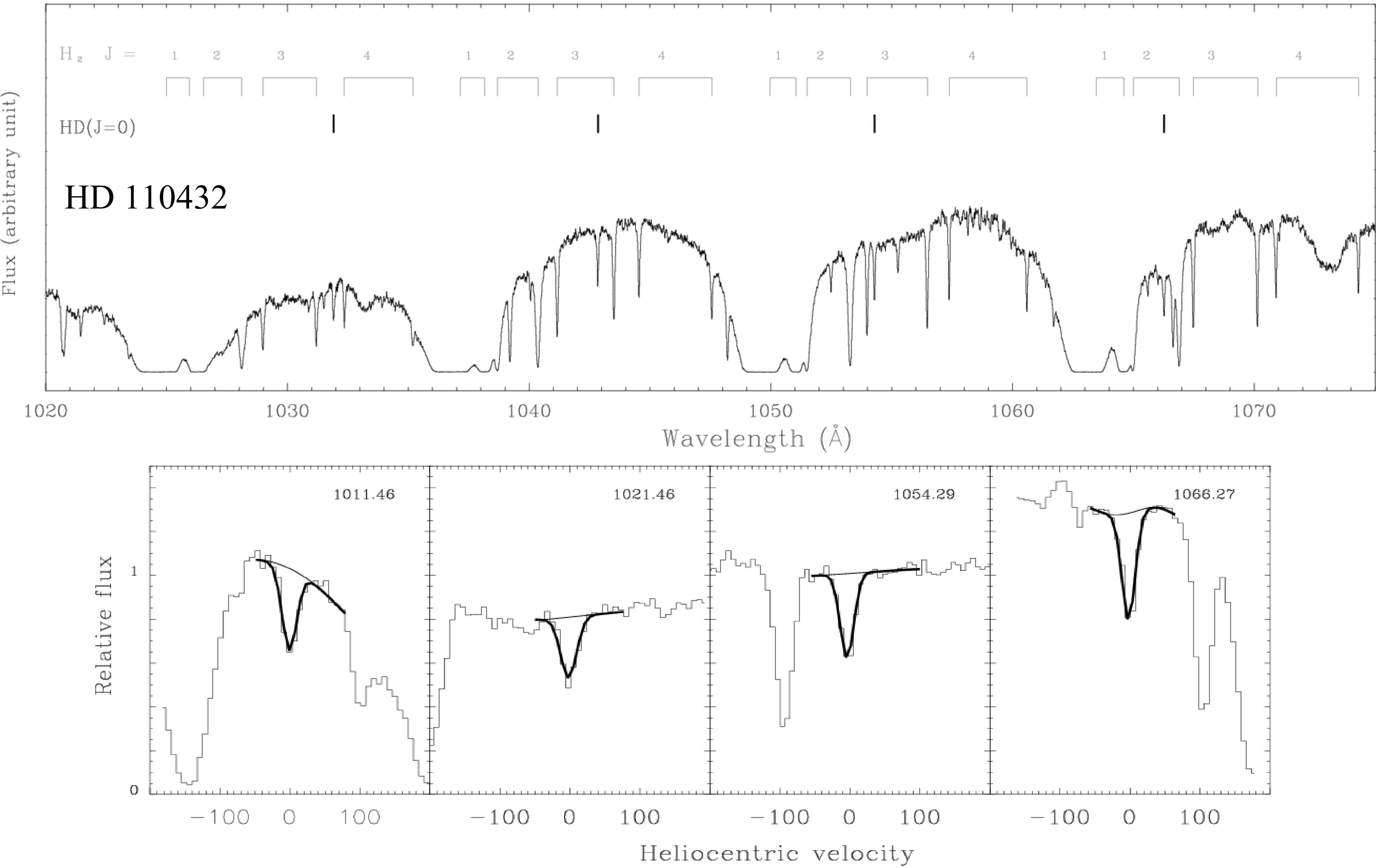
- HD/2H_2 gives D/H only for f ~ 1
- in the other cases gives a lower limit

For diffuse clouds with f < 1, to determine D/H it is recommended to measure both : N(D)/N(H) and N(HD)/2N(H_2)



Observations

Lacour et al. (A&A, 2005)



Observations

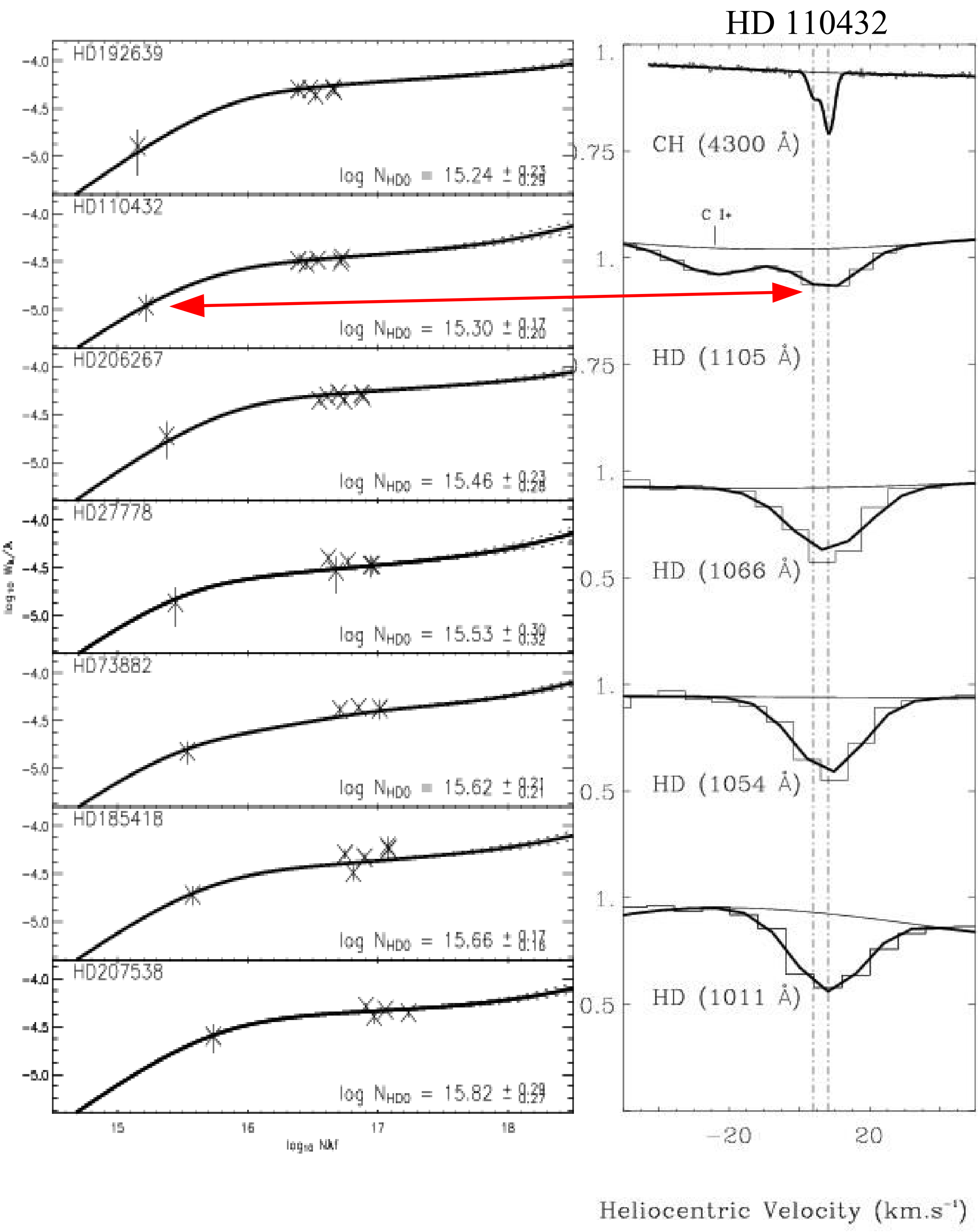
Copernicus : 10 detections
FUSE : +100 detections

⇨Probleme of the saturation of the lines

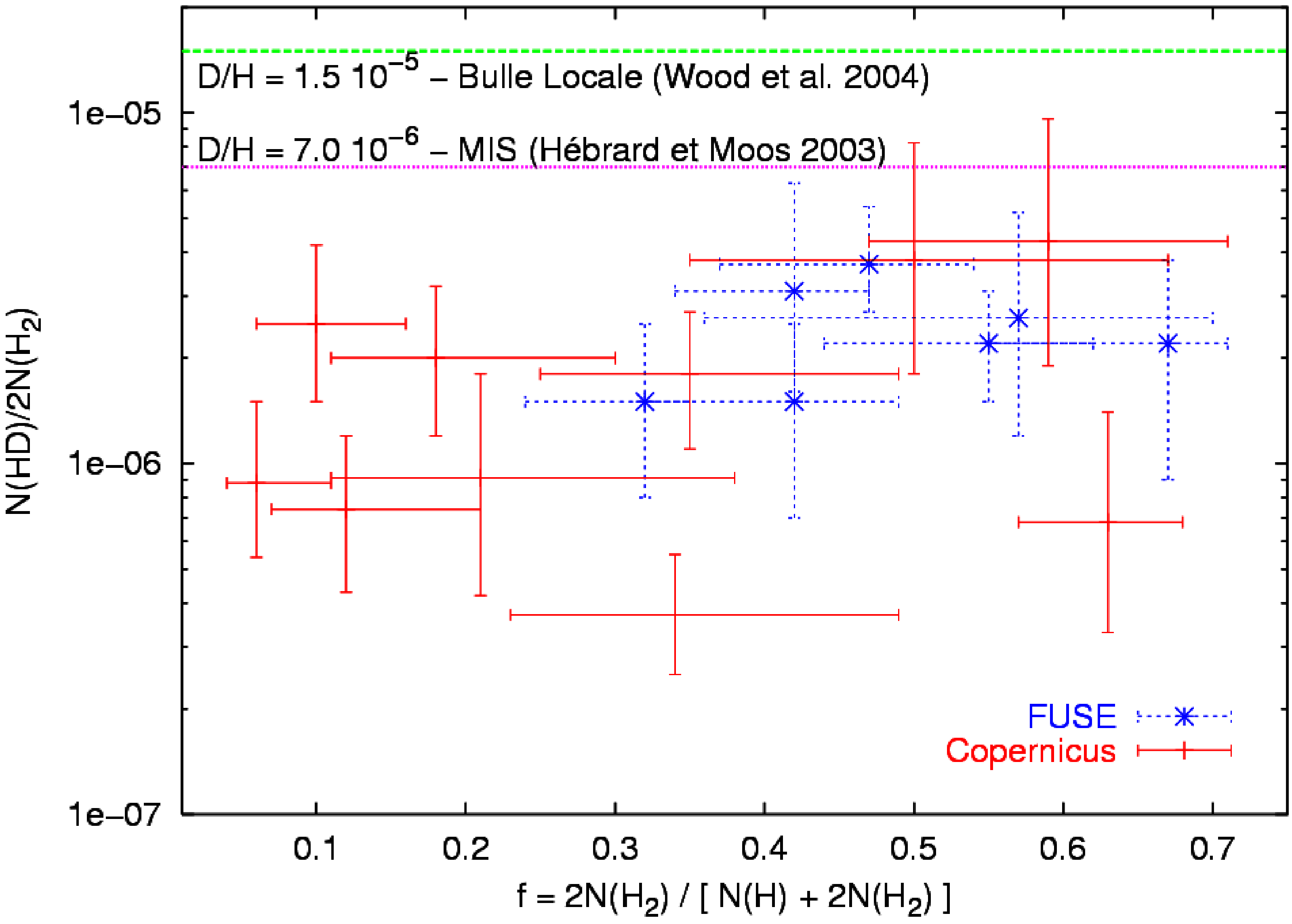
① Complementary observations
at Resolution = 1-2 km s^{-1}
ex : CH, K I

② Analysis by 2 methods
a) **Curve of growth**
b) **fit of lines** :
Owens (Martin Lemoine)

Analysis of 7 FUSE l.o.s.
Re-analyse Copernicus data



Results of the HD survey in our Galaxy



HD/$2H_2$ lower limit to D/H

It seems difficult to conclude on D/H from N(HD)/N(H_2) ...

1) **Problem of the molecular fraction**

2) **Variation of the ratio D/H**

Variations of N(D)/N(H) :

Local bubble	:	D/H = 1.5 (-5)	(Wood et al. 2004)
MIS	:	D/H = 0.7 (-5)	(Hébrard et Moos 2003)

3) **Depletion of deuterium on dust** (B. Draine 2004)

- ✓ no variations of O/H are observed but D/H vary :

Deuterium may be depleted on dust

- ✓ This could be an efficient depletion due to the difference of zero point level energy between H and D

less D to form HD

The next steps ...

1) HD survey towards more targets

2) excitation of H_2

3) FUSE results for diffuse clouds at high galactic latitudes
better understanding of damped Lyman alpha systems with H_2
(Tumlinson et al. - in preparation)

Up to now ...

Magellan : Similarities with the Galaxy even with a lower metallicity
Galaxy : H_2 survey ⇨ **Confirmation of Copernicus results**
HD ⇨ **Lower limit D/H**

Thanks to Copernicus and FUSE we know N(H_2) on many l.o.s
H_2 + other species ⇨ many constaints

Part III : Determination of physical conditions

Structure of diffuse clouds

- Some molecules
  - seem to need high densities to exist : CO, C_2, C_3
  - present variations in column densities at small scales
    H_2CO, OH, HCO^+ (Moore & Marscher 1995 – Liszt & Lucas 2000)

- But no variations for dust (Thoraval & al. 1995)

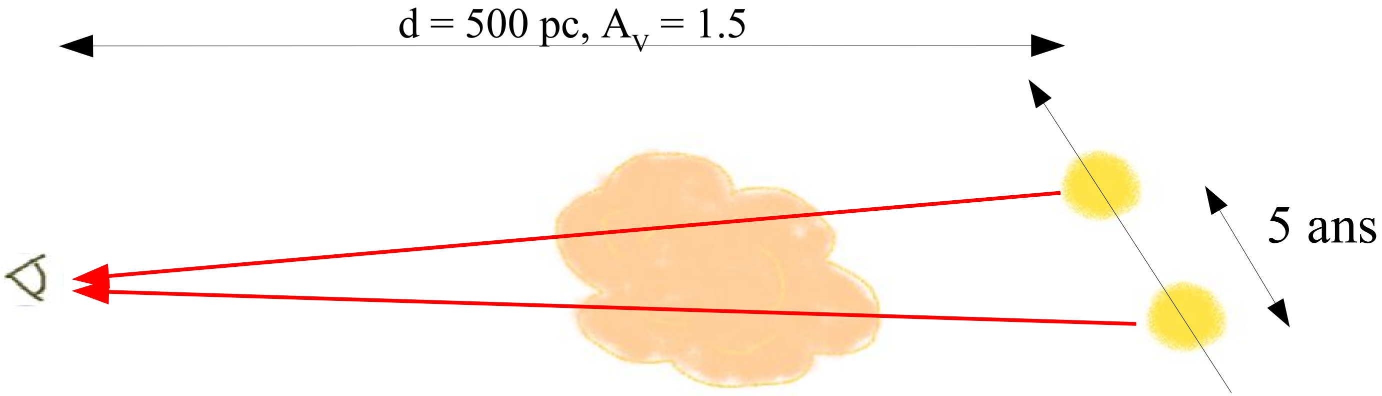
What about H_2 ?

1) If $N(H_2)$ varies ⟶ dust does not vary because of its inertia

2) If $N(H_2)$ does not vary ⟶ minor species may probe chemical inhomogeneities

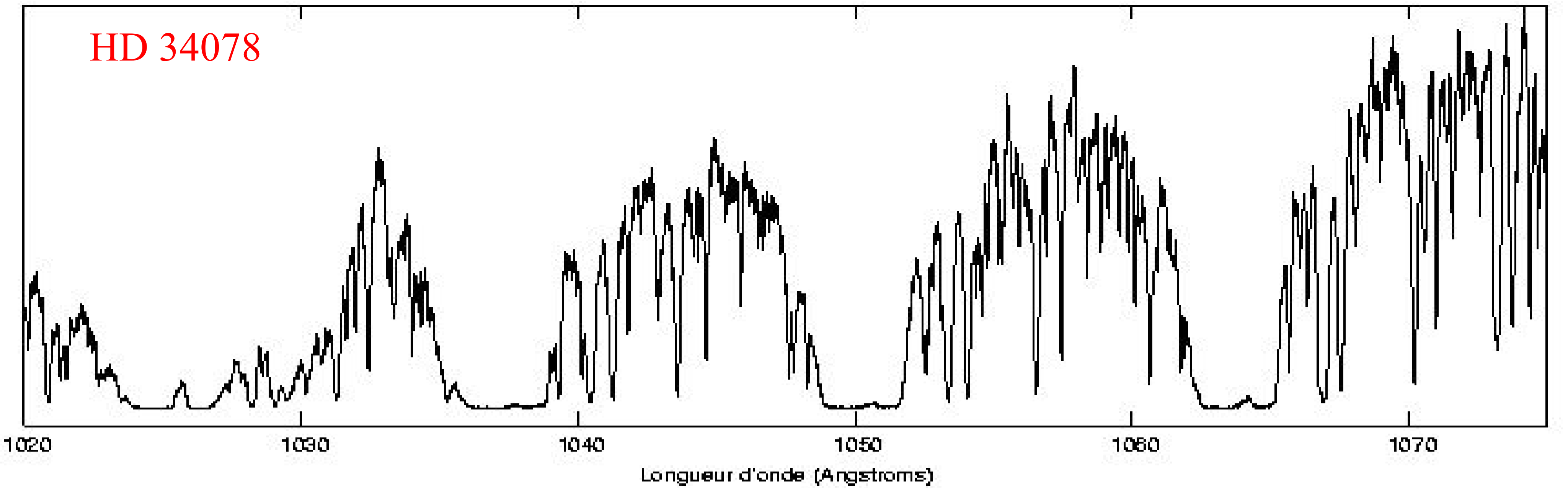
FUSE observations towards HD 34078 (P. Boissé et al. A&A, 2005)

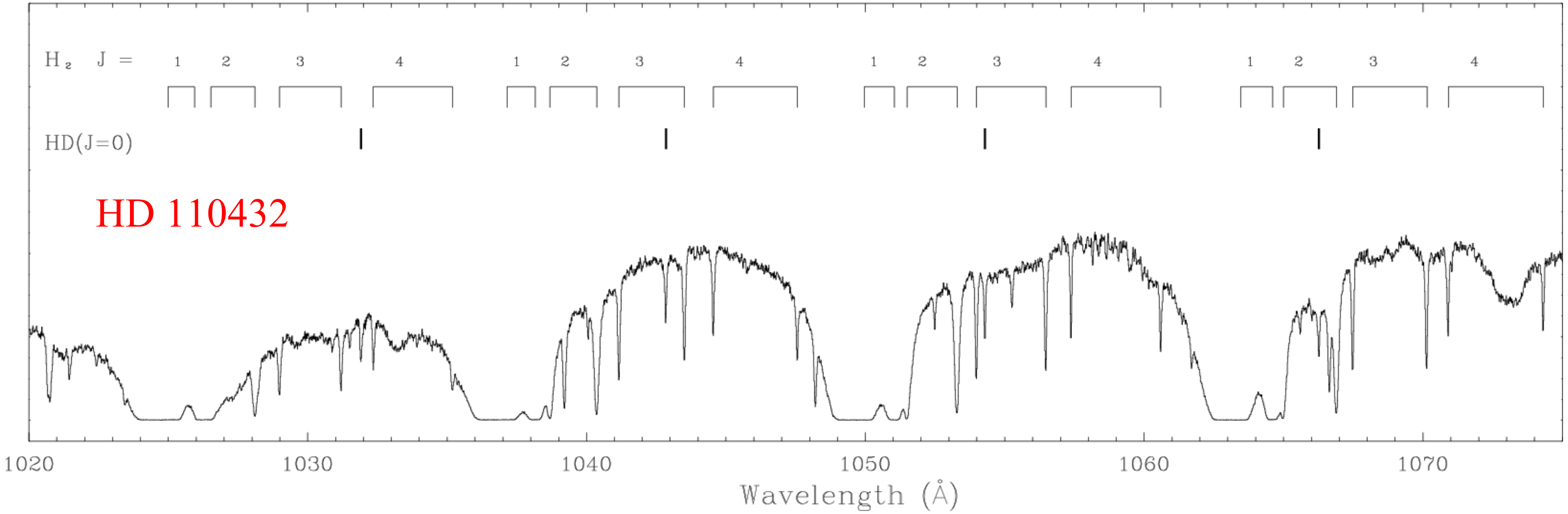
- HD 34078 (AE Aurigae) : **runaway star** - $v_t = 100$ km s^{-1}
  Line of sight observed by FUSE for 5 years

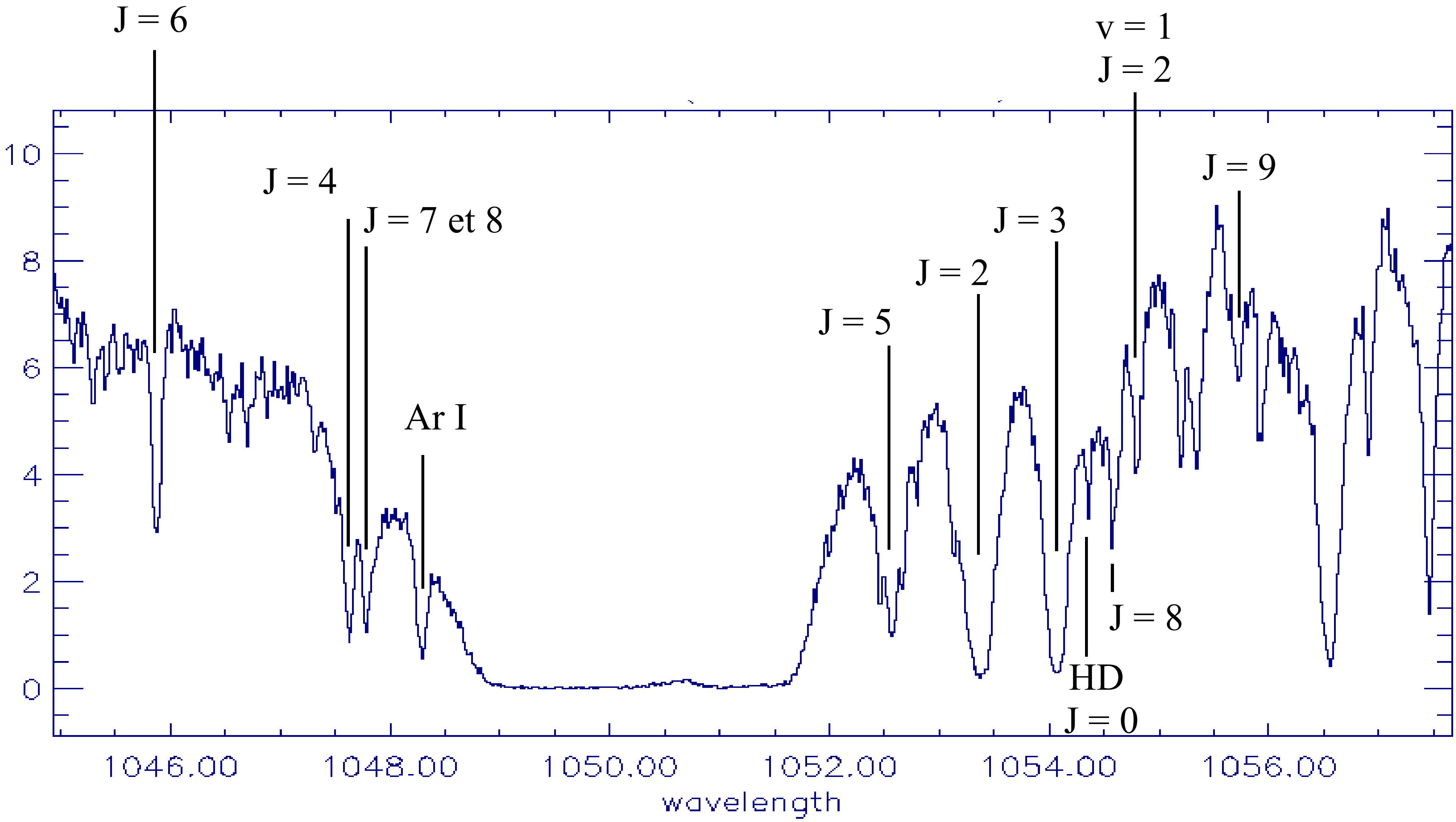


- Well studied line of sight :
  - H I and CO -- IUE : Mc Lachlan & Nandy (1981)
  - CH, CN and C_2 -- S. Federman et al. (1994)
  - CH and CH^+ -- M. Allen (1994)
  - CH and CH^+ -- E. Rollinde and P. Boissé (2003)
  - OH -- CFHT/Gecko – 2002
  - C_3 -- Oka et al. (2003)

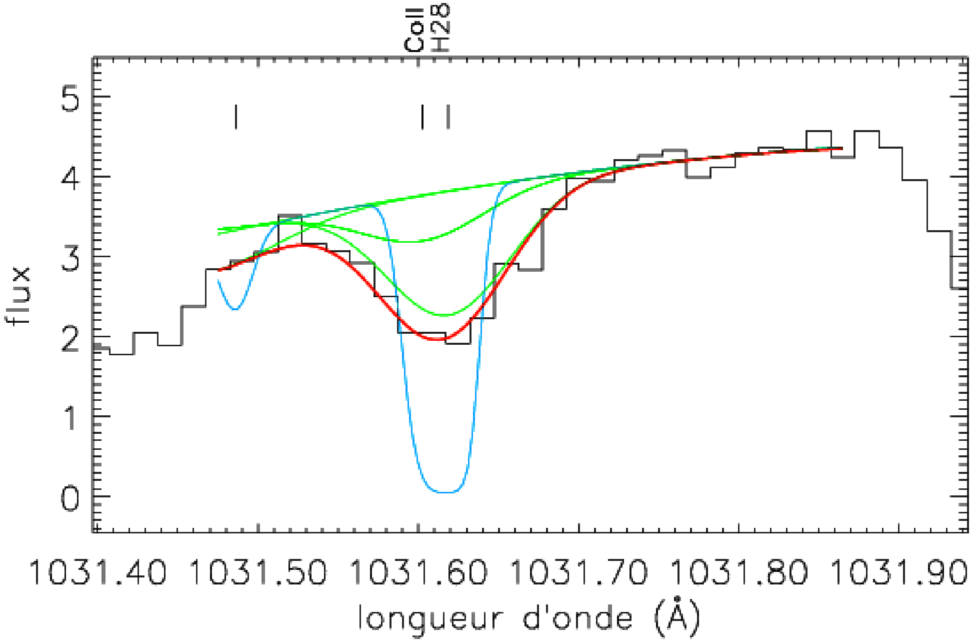
S/B = 30 par pixel de 15 mÅ

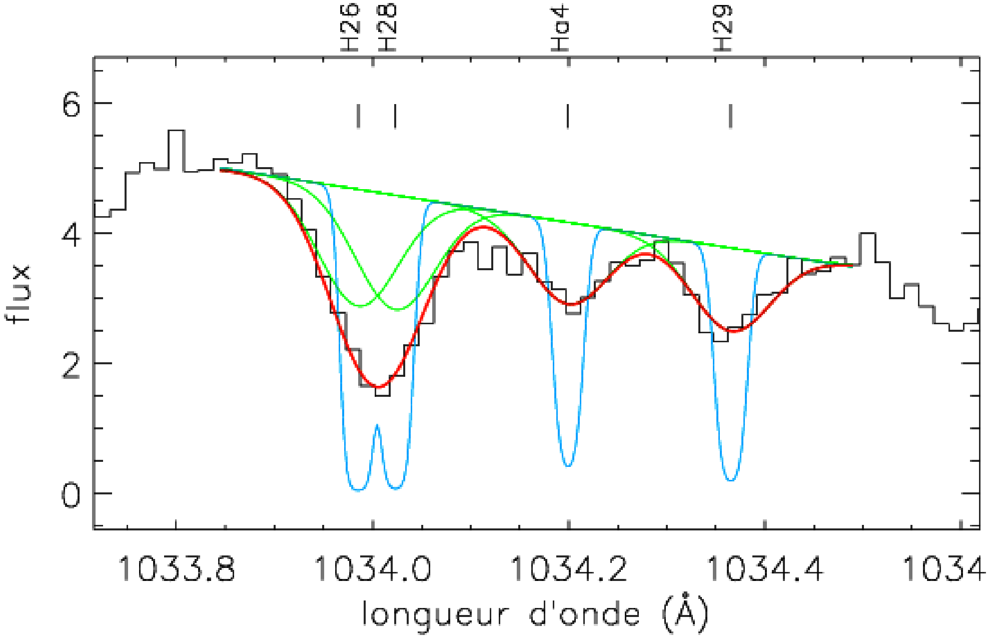


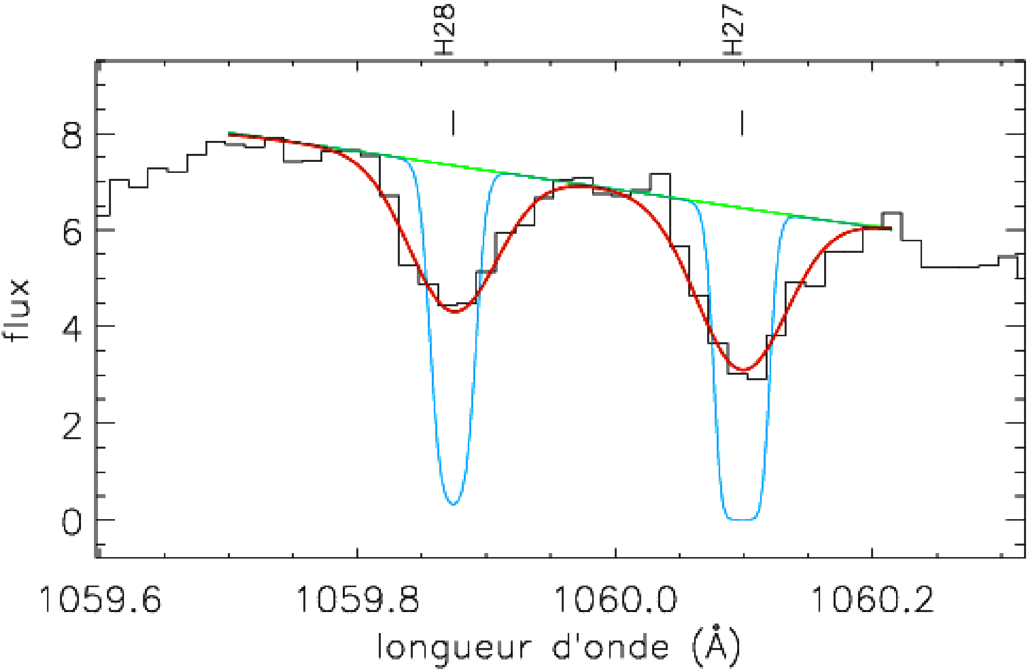


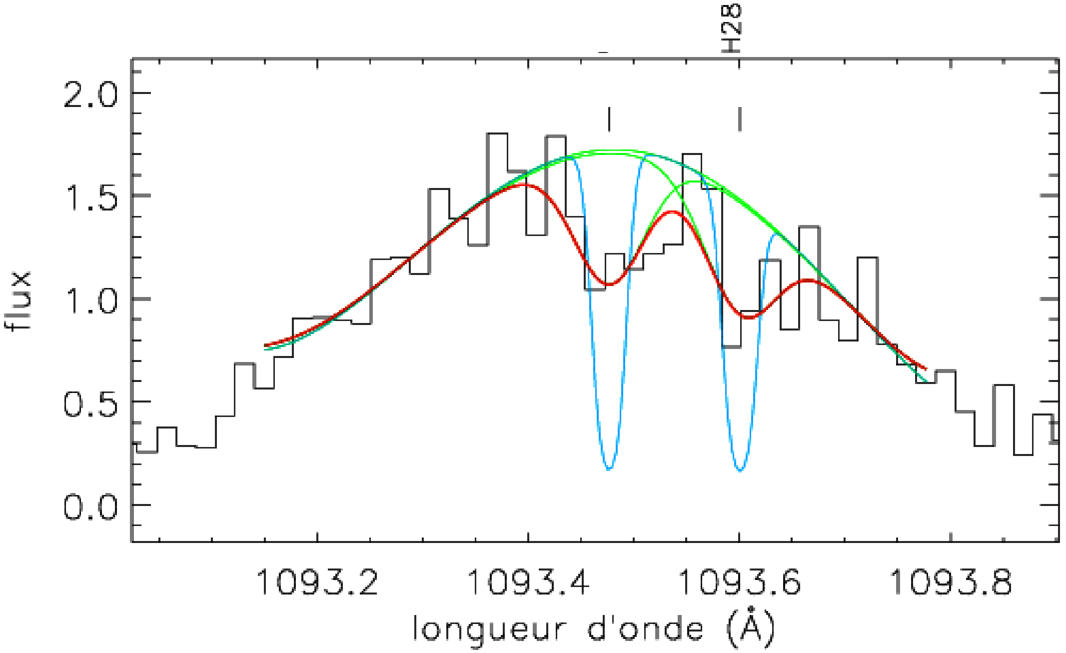


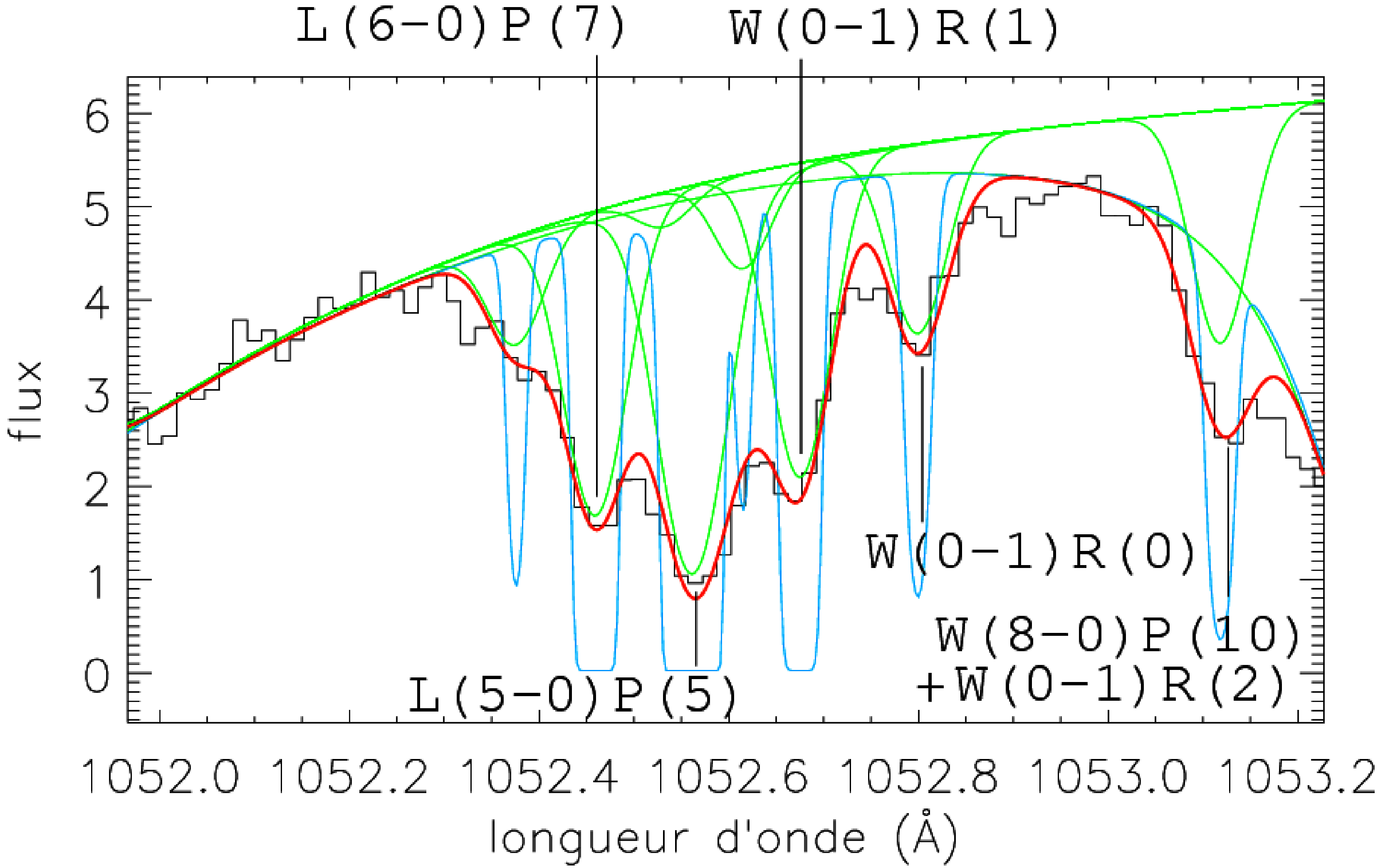
J = 6
J = 4
J = 7 et 8
Ar I
J = 5
J = 2
J = 3
v = 1
J = 2
J = 9
J = 8
HD
J = 0
10
8
6
4
2
0
1046.00
1048.00
1050.00
1052.00
1054.00
1056.00
wavelength


CoII
H28
5
4
3
2
1
0
flux
1031.40
1031.50
1031.60
1031.70
1031.80
1031.90
longueur d'onde (Å)


H26
H28
Ha4
H29
6
4
2
0
flux
1033.8
1034.0
1034.2
1034.4
1034.6
longueur d'onde (Å)


H28
H27
8
6
4
2
0
flux
1059.6
1059.8
1060.0
1060.2
longueur d'onde (Å)


H28
2.0
1.5
1.0
0.5
0.0
flux
1093.2
1093.4
1093.6
1093.8
longueur d'onde (Å)


L(6−0)P(7)
W(0−1)R(1)
W(0−1)R(0)
W(8−0)P(10)
+W(0−1)R(2)
L(5−0)P(5)
flux
0
1
2
3
4
5
6
1052.0
1052.2
1052.4
1052.6
1052.8
1053.0
1053.2
longueur d'onde (Å)

H_2 detection

$N(H_2) = 6.4\times10^{20}$, $N(H\ I) = 1.7\times10^{21}$, $f = 0.4$

- the **18 first ro-vibrational levels of H_2 are detected**
  - maximum pure rotationnal level : J = 11 (E = 10 261 K)
  - maximum ro-vibrationnal level : v = 1, J = 5

- Upper limits up to J = 13

- Other detection of very excited H_2

  - HST observations towards HD 37903 (Meyer et al. 2001)

    99 rovibrationnal levels
    14 vibrational levels
    ↳ excitation by the star at 0.5 pc from the cloud

HD detection

- 7 lines of HD, J = 0 are detected

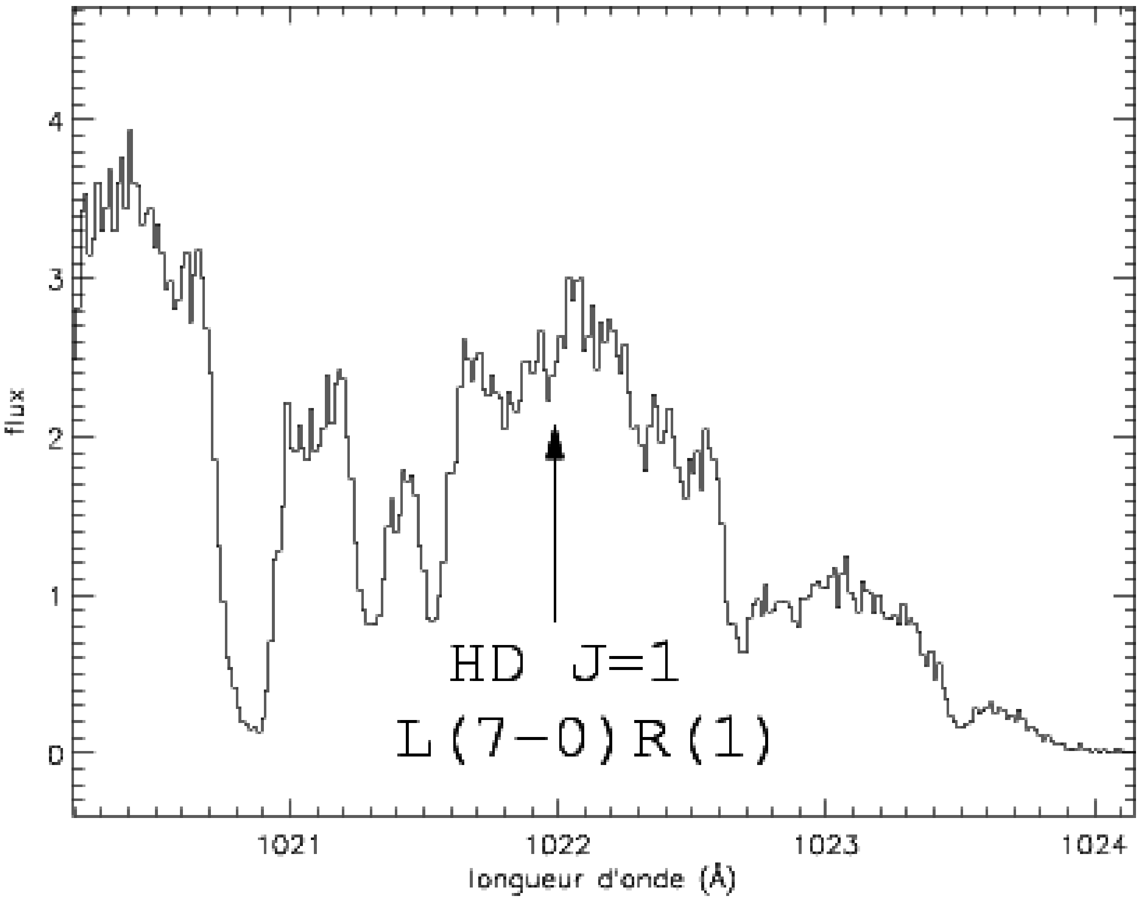
but : most of them are blended with other lines
2 nice lines give very different N(HD) :

1031.91 Å : N(HD) = $2.8\times10^{14} - 3.0\times10^{15}$ cm^{-2}
1066.27 Å : N(HD) = $2.0\times10^{16} - 7.0\times10^{16}$ cm^{-2}

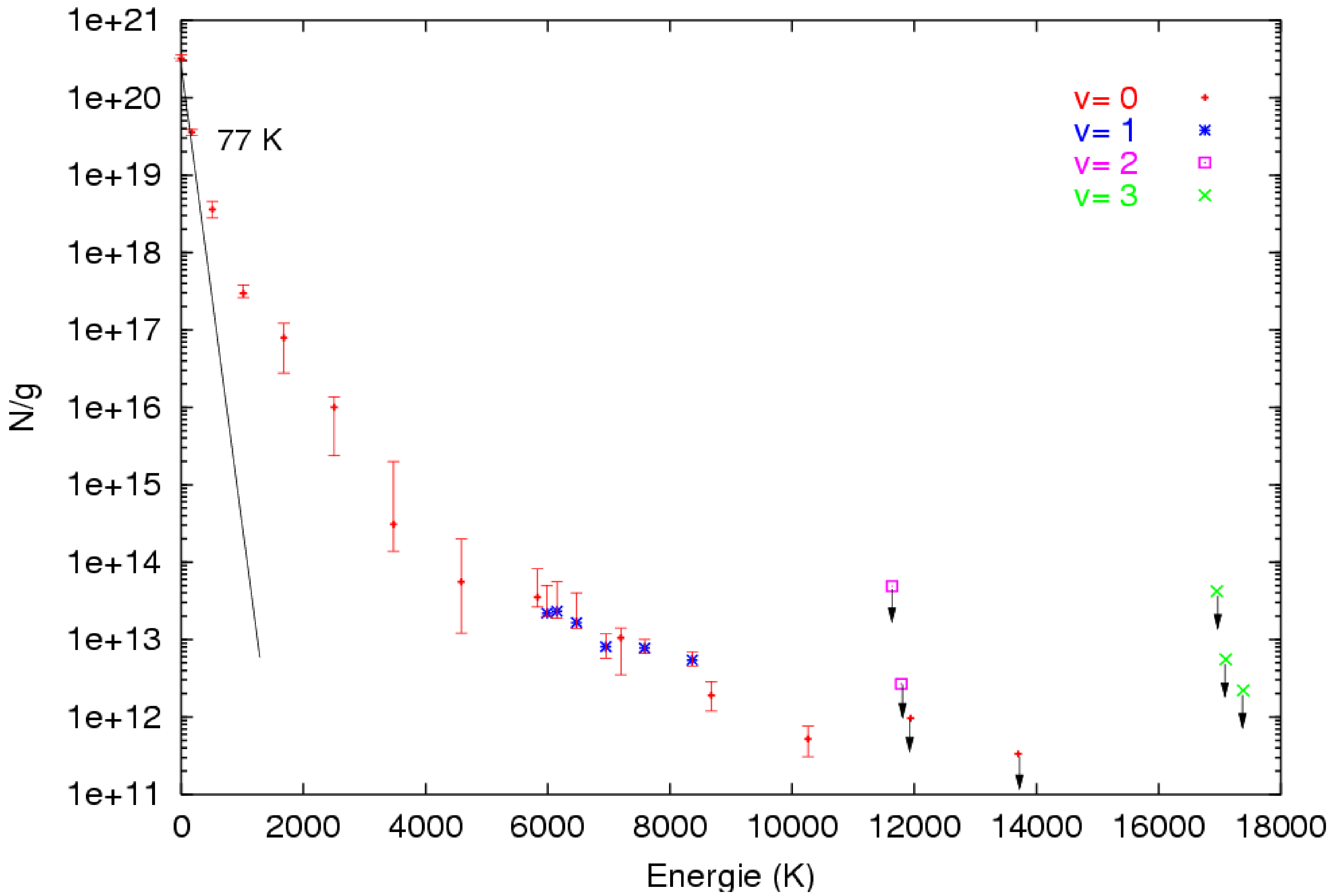
- 1 line of HD, J = 1 at 1021.916 A

N(HD, J=1) $\approx 5 \times 10^{13}$ cm^{-2}

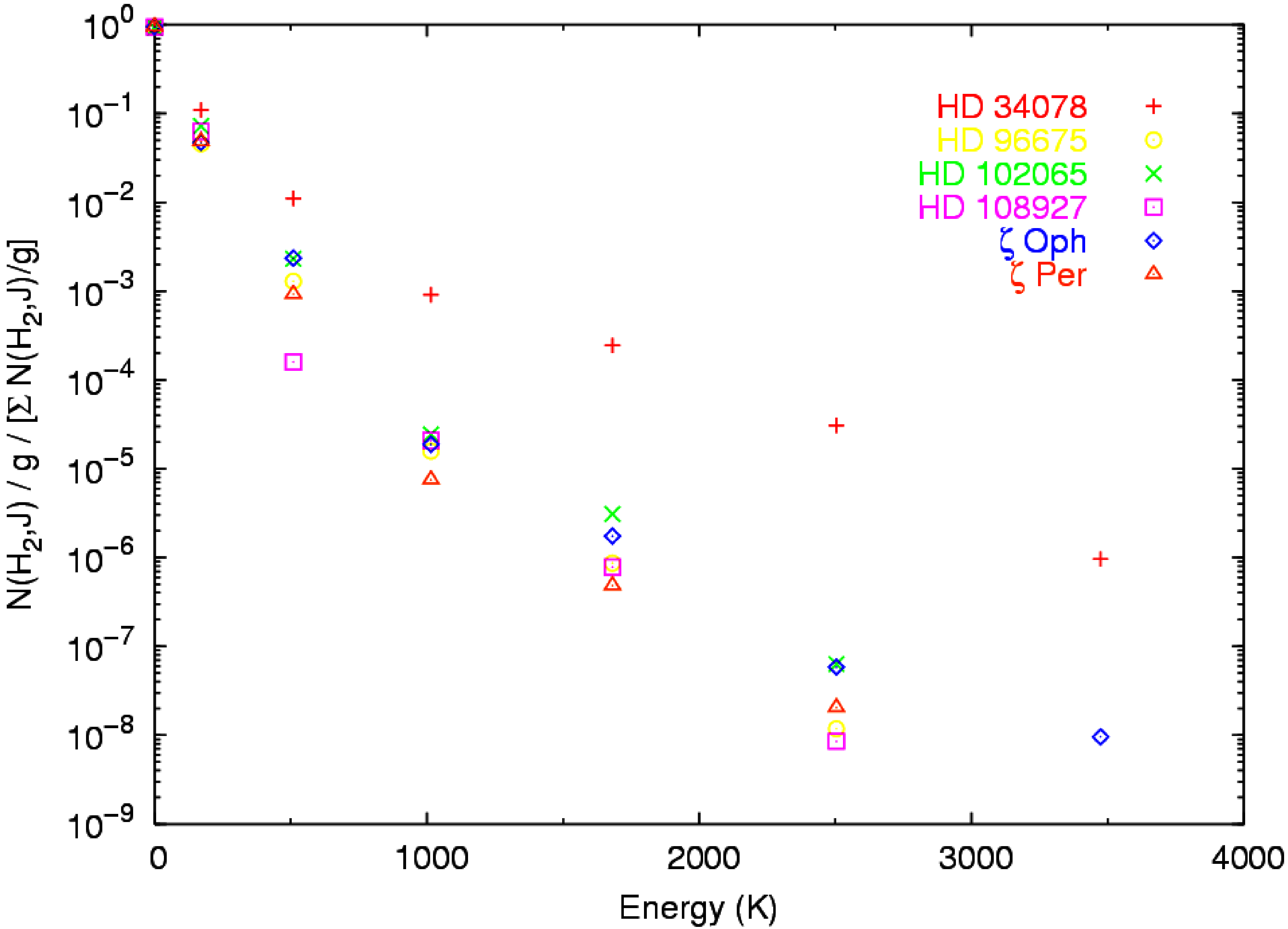
⇨ $T_{01} \approx 40$ K



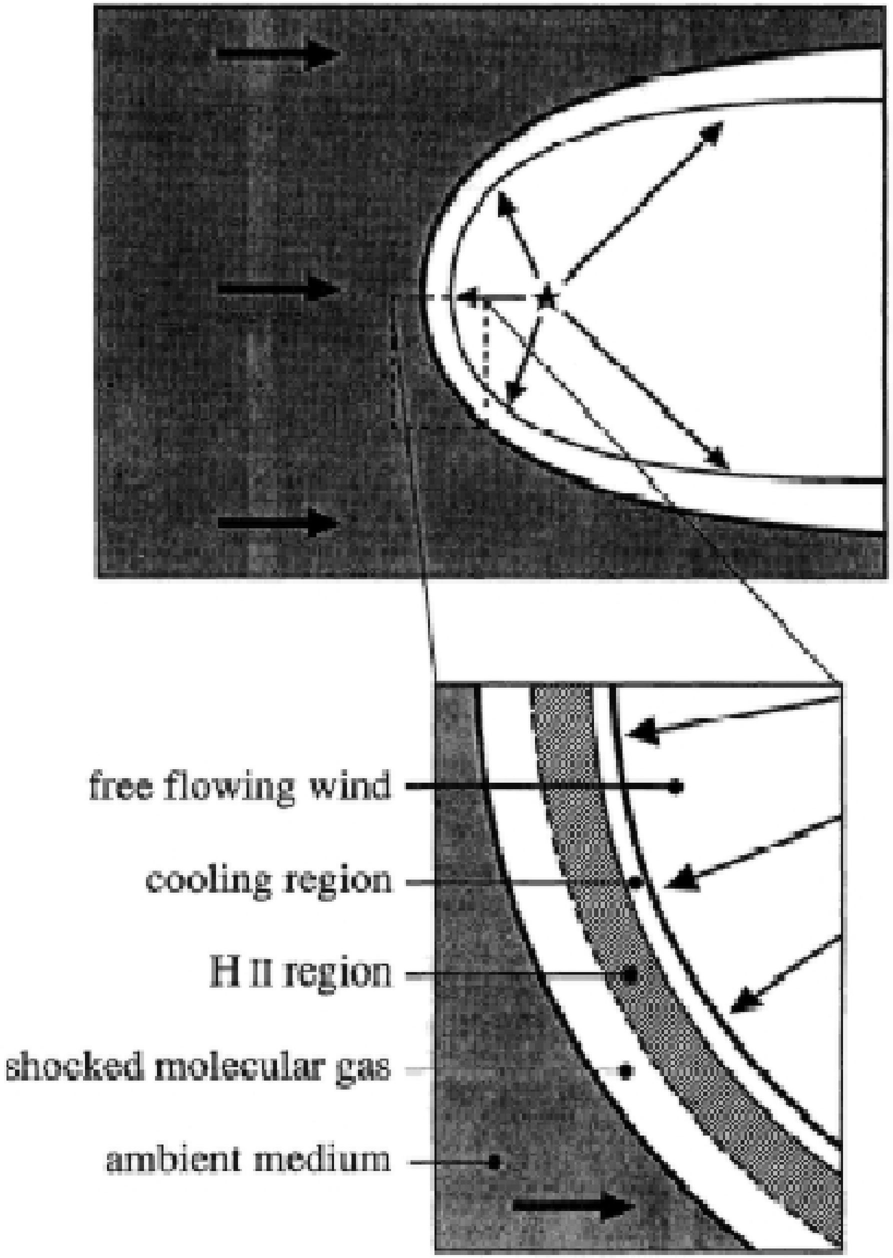
Excitation diagram



Comparison of excitation diagrams



HST picture in Orion



van Buren et al. (1991)

Model of the line of sight towards HD 34078

- Diffuse cloud

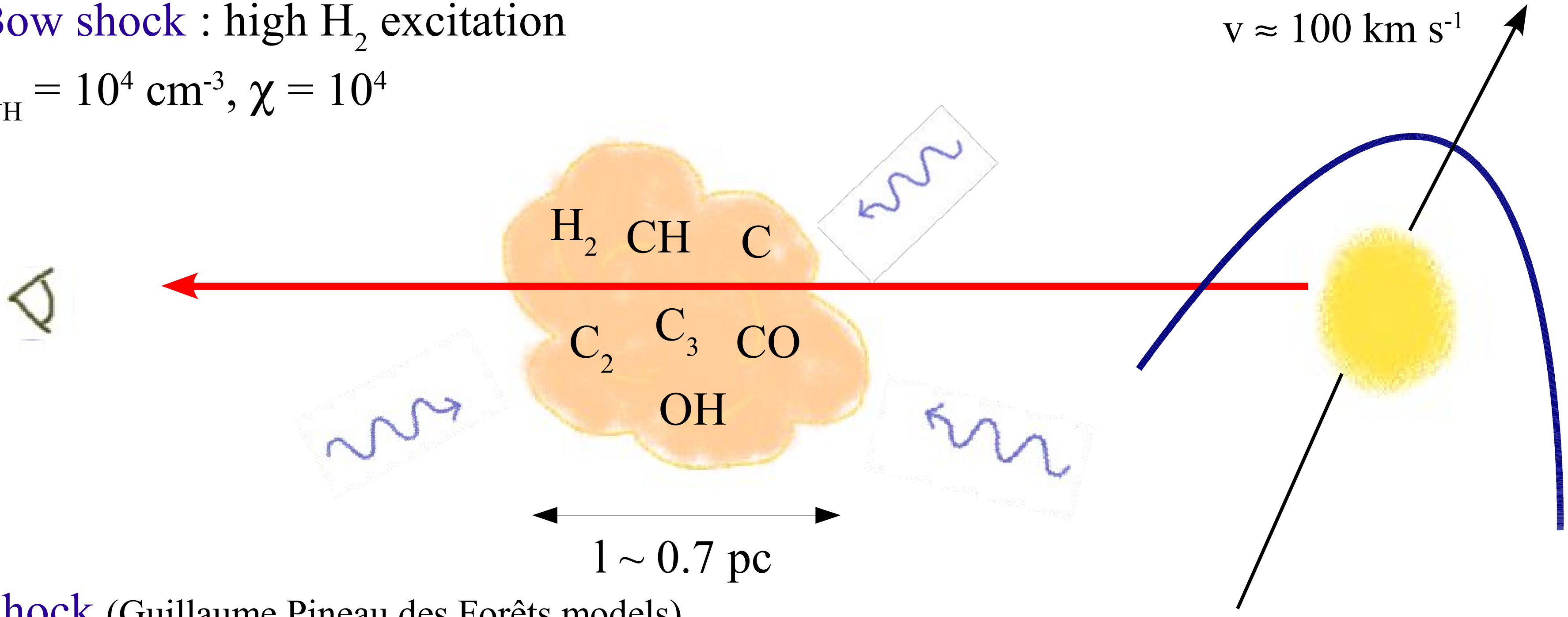
  H_2 J = 0, 1 → $T_{kin} = 77$ K

  C → $n_H = 700$ cm^{-3}

  and the molecules CH, C_2, C_3, CN, CO, OH

- Bow shock : high H_2 excitation

  $n_H = 10^4$ cm^{-3}, $\chi = 10^4$



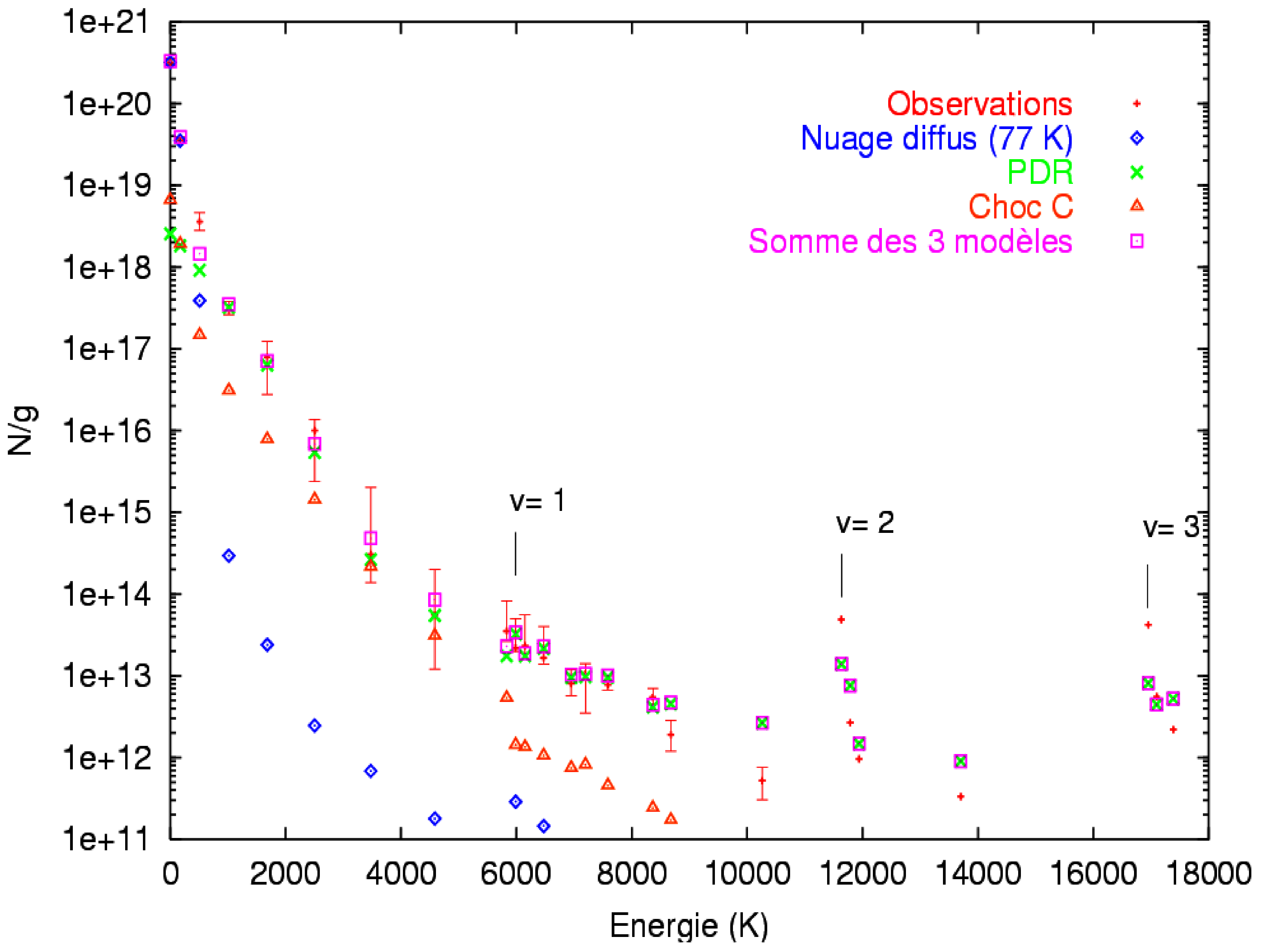
- C shock (Guillaume Pineau des Forêts models)

  required to explain n(CH^+)

  v = 25 km s^{-1}, B = 7 µG, pre-shock density = 20 cm^{-3}

Espèces	**Observations**			**Modèle**			
	moyenne	minimum	maximum	**nuage diffus**	**PDR**	**choc C**	**total**
H	**1.7E21**	1.5E21	1.9E21	2.8E19	2.0E21	-	**2.0E21**
H_2	**6.4E20**	6.0E20	6.9E20	6.4E20	3.6E19	-	**6.7E20**
HD	**1.0E15**	-	-	9.0E15	6.0E13	?	**9.0E15**
OH	**3.5E13**	1.4E13	5.6E13	1.4E13	5.9E11	2.9E14	**2.6E14**
CH	**7.2E13**	6.3E13	7.4E13	5.2E13	7.9E9	4.1E12	**5.6E13**
CH^+	**6.6E13**	6.0E13	7.1E13	2.0E10	4.9E11	6.0E13	**6.0E13**
C_2	**5.8E13**	-	-	2.4E13	1.8E7	3.0E10	**2.4E13**
CN	**2.1E12**	-	-	2.4E12	5.9E8	5.8E11	**3.0E12**
CO	**5.7E14**	4.6E14	7.2E14	7.4E14	1.0E11	-	**7.4E14**
C I	**9.4E15**	3.6E15	1.7E16	2.3E15	2.4E12	-	**2.3E15**
C I *	**5.8E15**	1.6E15	5.8E15	3.8E15	7.0E12	-	**3.8E15**
C I **	**2.2E15**	1.1E15	4.0E15	1.9E15	1.0E13	-	**1.9E15**

The model reproduce relatively well the observed column densities



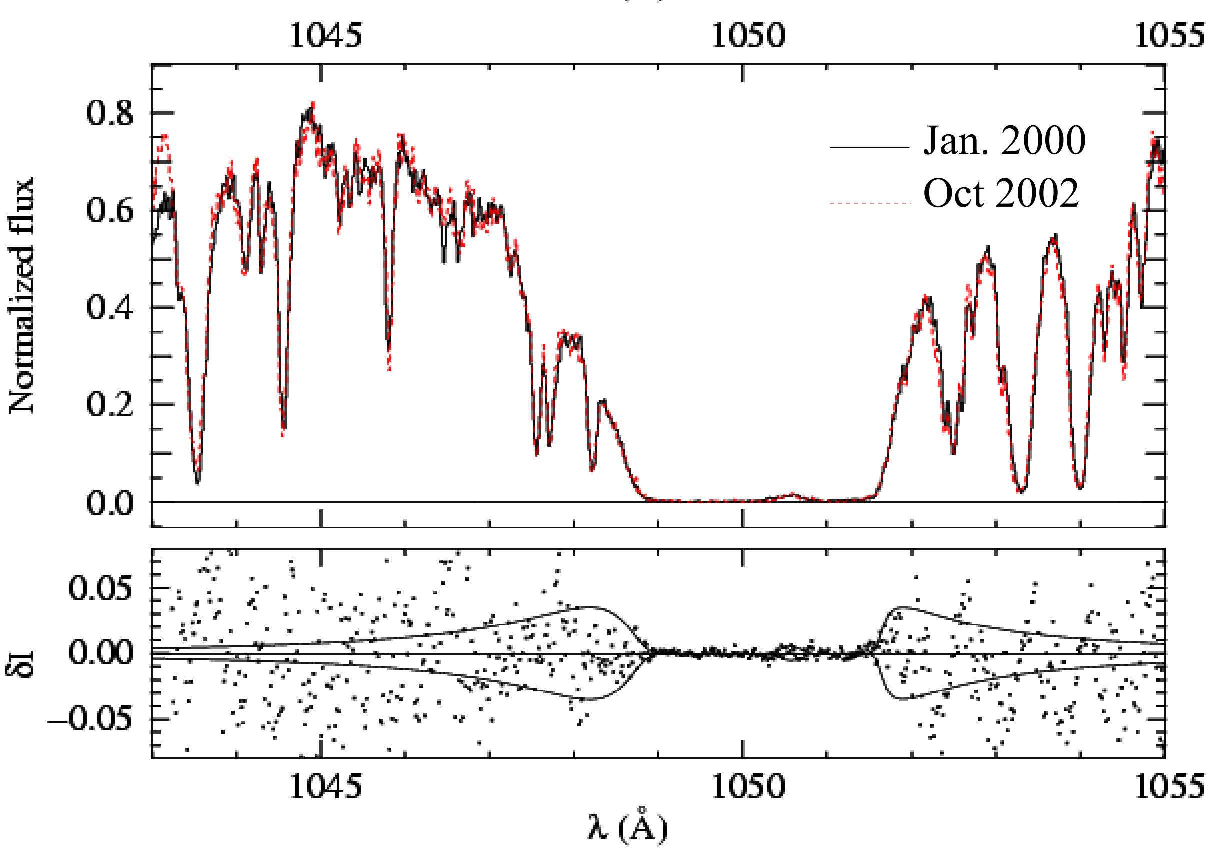
Observations
Nuage diffus (77 K)
PDR
Choc C
Somme des 3 modèles
v= 1
v= 2
v= 3
N/g
Energie (K)
1e+21
1e+20
1e+19
1e+18
1e+17
1e+16
1e+15
1e+14
1e+13
1e+12
1e+11
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

Comparison of spectra

- **Variation in H_2 lines**
  - wings of damped systems
  - optically thin lines

comparison on 5 years

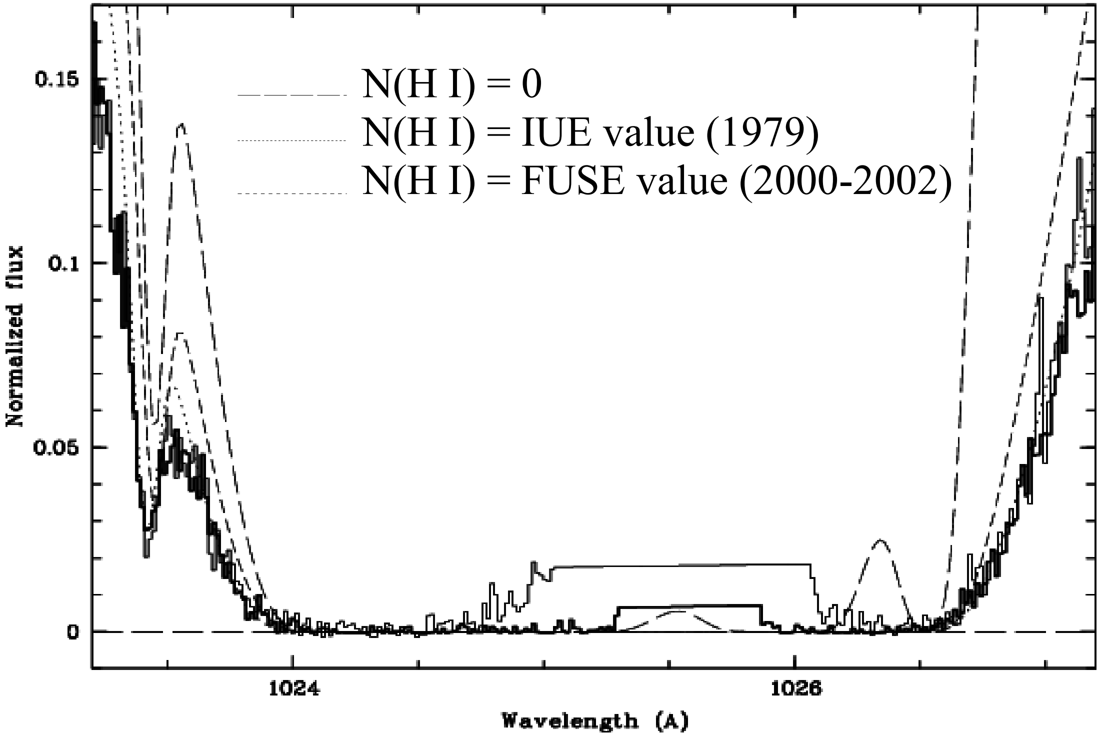
No significant differences in the spectra



- **Variation in Lyman β**

comparison on 21 years (IUE – FUSE)
re-analysis of IUE spectrum (1979)

variation of 1.8% per year

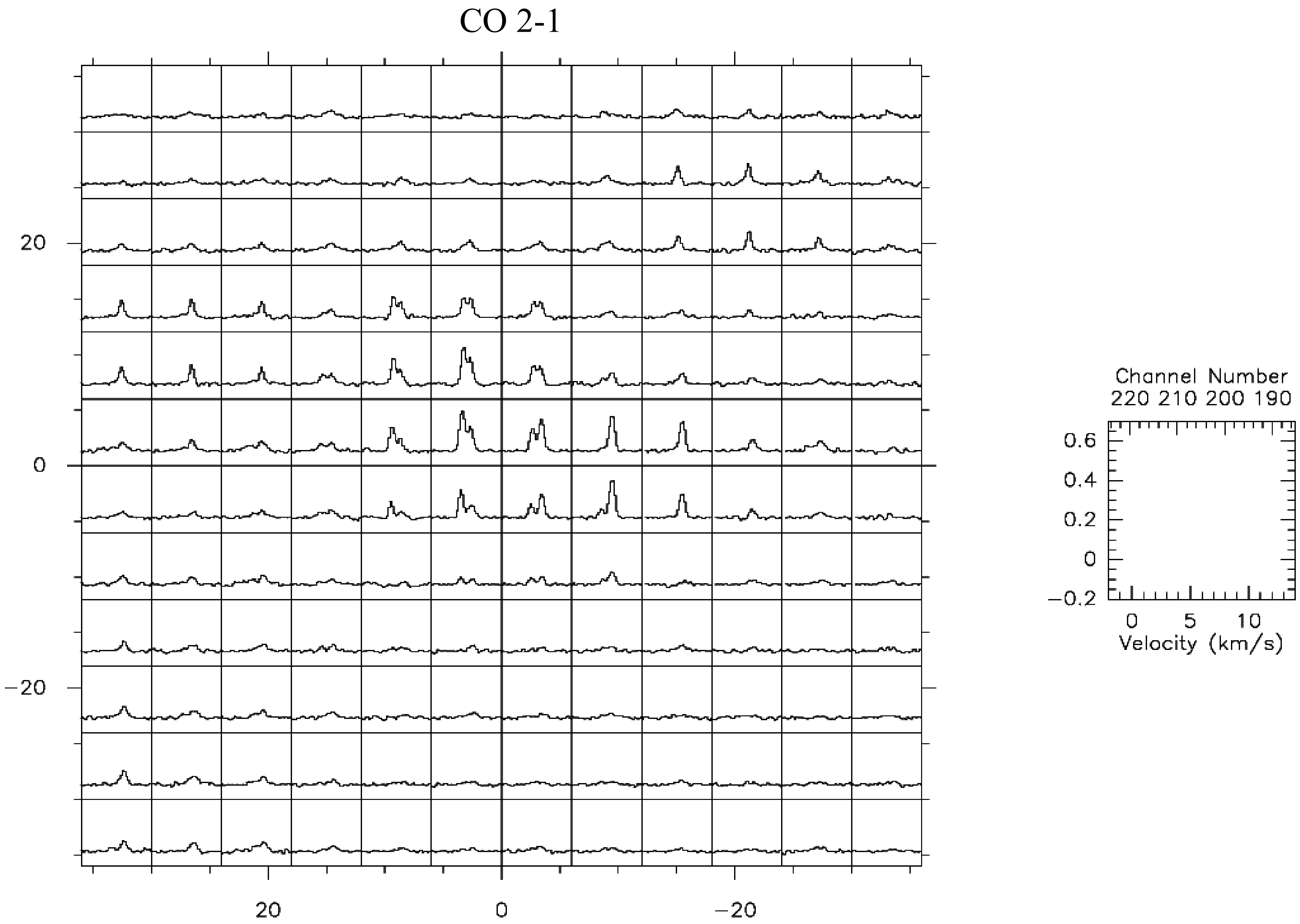


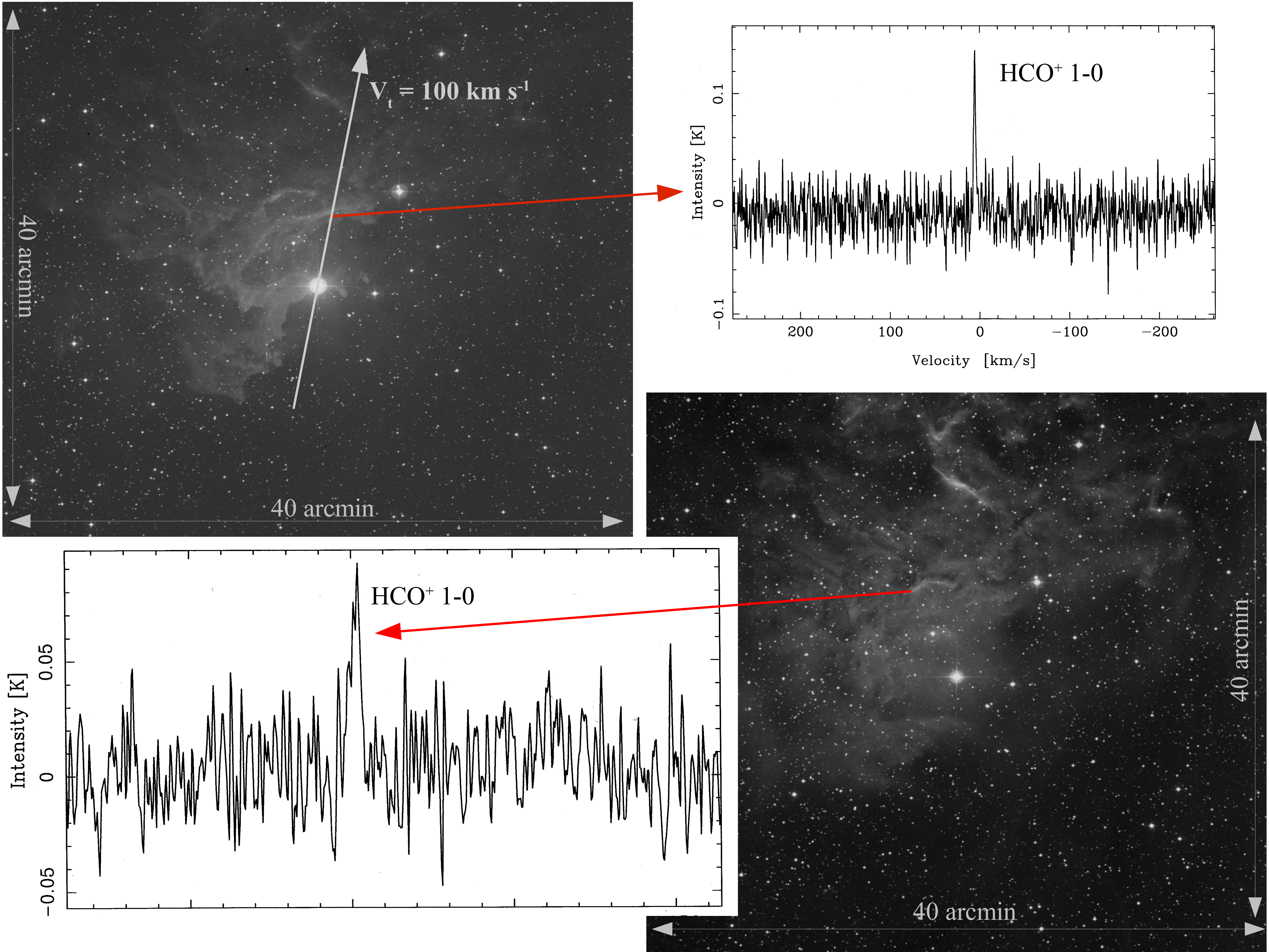
- **Variation of N(CH)** (Rollinde et al. 2003)

comparison on 12 years

Variation of 1.7% per year

IRAM/HERA observations towards HD34078




V_t = 100 km s^{-1}
40 arcmin
40 arcmin
HCO$^+$ 1-0
Intensity [K]
0.1
0
−0.1
200
100
0
−100
−200
Velocity [km/s]
HCO$^+$ 1-0
Intensity [K]
0.05
0
−0.05
40 arcmin
40 arcmin

The problem of the ionization

The formation of many molecules is initiated by cosmic rays : OH, HD, H_3^+, HCO^+, NH

ion-neutral reactions are favoured

- thermodynamically : no activation threshold
- kinetically : neutral-neutral reaction : $k = 10^{-11}$ cm^3 s^{-1}
  ion-neutral reaction : $k = 10^{-9}$ cm^3 s^{-1}

fundamental to know precisely the ionization rate

standard value : $\zeta =$ **$1\text{-}5\times10^{-17}$ s^{-1}**

This value is incompatible with the detection of H_3^+ on diffuse l.o.s

$$H_2 + \text{cosmic ray} \longrightarrow H_2^+ + e^- \qquad k = \gamma\,\zeta \quad (s^{-1})$$

$$H_2^+ + H_2 \longrightarrow H_3^+ + H$$

several possibilities :

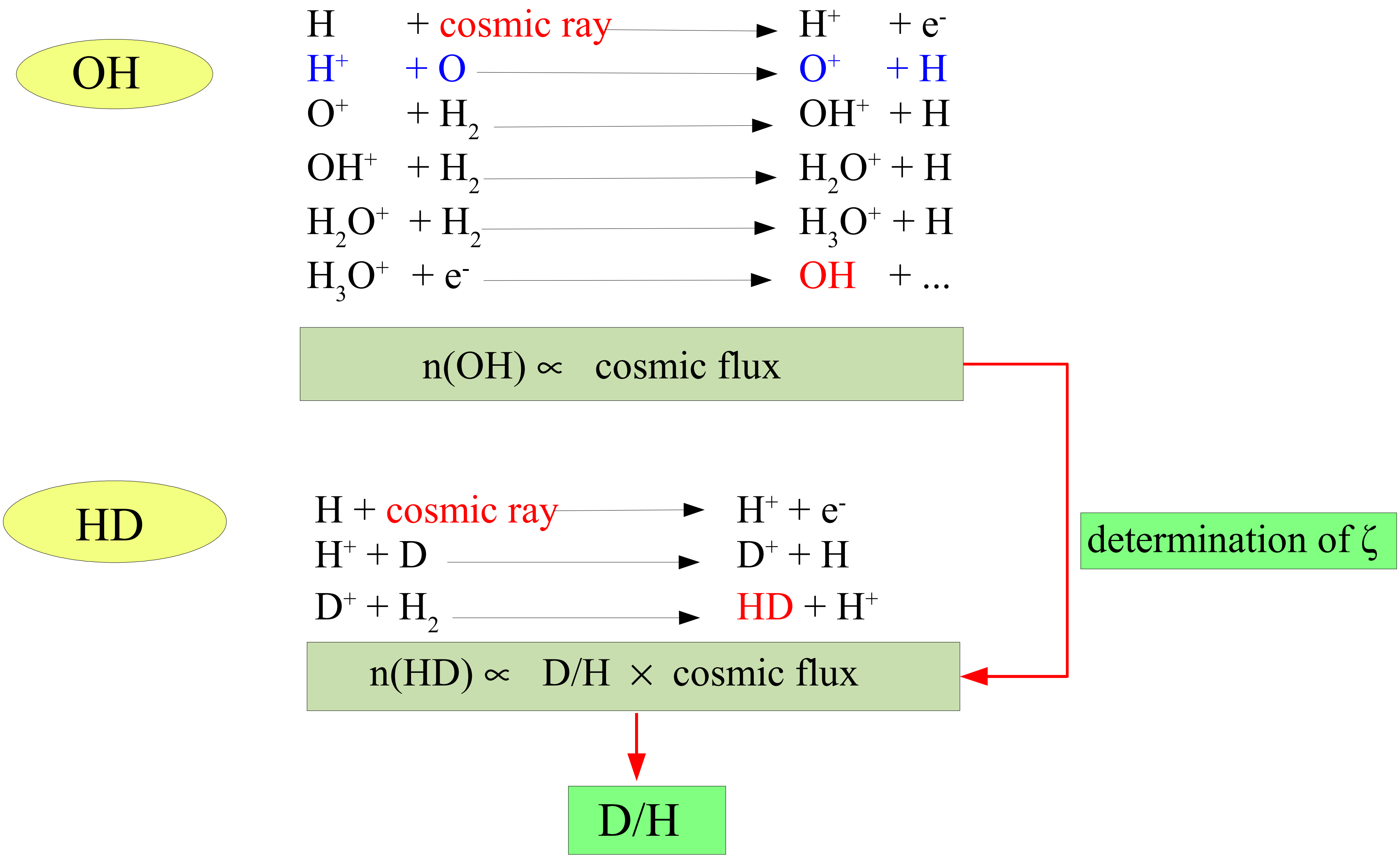
1) huge diffuse clouds : nearly extend throughout the path between the star and earth (Geballe et al. 1999)

2) clumpy medium : model for Cygnus OB2 No 12. (Cecchi-Pestellini & Dalgarno 2000)

3) higher ionization rate of the medium (McCall et al. 2003)

The flux of cosmic rays and the ratio D/H

(Black et Dalgarno 1973, Black et al. 1978, Federman et al. 1996, Le Petit et al. 2001)



OH

$H + \text{cosmic ray} \rightarrow H^+ + e^-$

$H^+ + O \rightarrow O^+ + H$

$O^+ + H_2 \rightarrow OH^+ + H$

$OH^+ + H_2 \rightarrow H_2O^+ + H$

$H_2O^+ + H_2 \rightarrow H_3O^+ + H$

$H_3O^+ + e^- \rightarrow OH + \ldots$

$n(OH) \propto \text{cosmic flux}$

determination of ζ

HD

$H + \text{cosmic ray} \rightarrow H^+ + e^-$

$H^+ + D \rightarrow D^+ + H$

$D^+ + H_2 \rightarrow HD + H^+$

$n(HD) \propto D/H \times \text{cosmic flux}$

D/H

The line of sight towards ζ Per

a very well studied line of sight :

- many observations
- a good test for models
  - Black, Hartquist and Dalgarno (1978)
    2 components model
    - cold zone : $T = 45$ K, $n_H = 267$ cm^{-3}
    - hot zone : $T = 120$ K, $n_H = 100$ cm^{-3}

    $\zeta = 2.2\times10^{-17}$ s^{-1}
  - Van Dishoeck and Black (1986)
    all constraints taken into account
    models with T and n profiles

    $\zeta = 4\text{-}7\times10^{-17}$ s^{-1}
  - Federman et al. (1996)
    From OH $\zeta = 1.7\times10^{-17}$ s^{-1}
  - McCall et al. Nature, 422, 500, 2003 → $N(H_3^+) = 8\times10^{13}$ cm^{-2}
    From H_3^+ $\zeta = 1.2\times10^{-15}$ s^{-1}

	Observations	
H	5.7(20)	7.1(20)
H_2	3.2(20)	7.1(20)
f	0.53	0.66
T_{01}	45	75
HD	2.0(15)	1.1(16)
H_3^+	8.0(13)	
C^+	1.8(17)	
C	2.9(15)	3.6(15)
CO	5.4(14)	
CH	1.9(13)	2.0(13)
CH^+	3.5(12)	
C_2	1.6(13)	2.2(13)
C_3	1.0(12)	
CN	2.7(12)	3.3(12)
NH	9.0(11)	
O	0.2(18)	1.0(18)
OH	4.0(13)	
S^+	1.7(16)	2.3(16)
S	1.5(13)	2.2(13)
Si^+	2.8(16)	2.8(14)

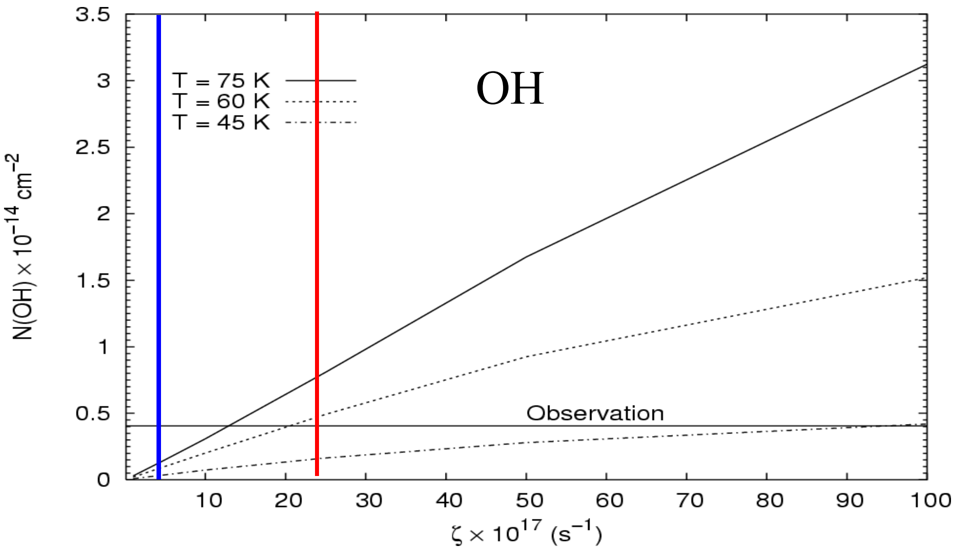
Model of the line of sight towards ζ Per

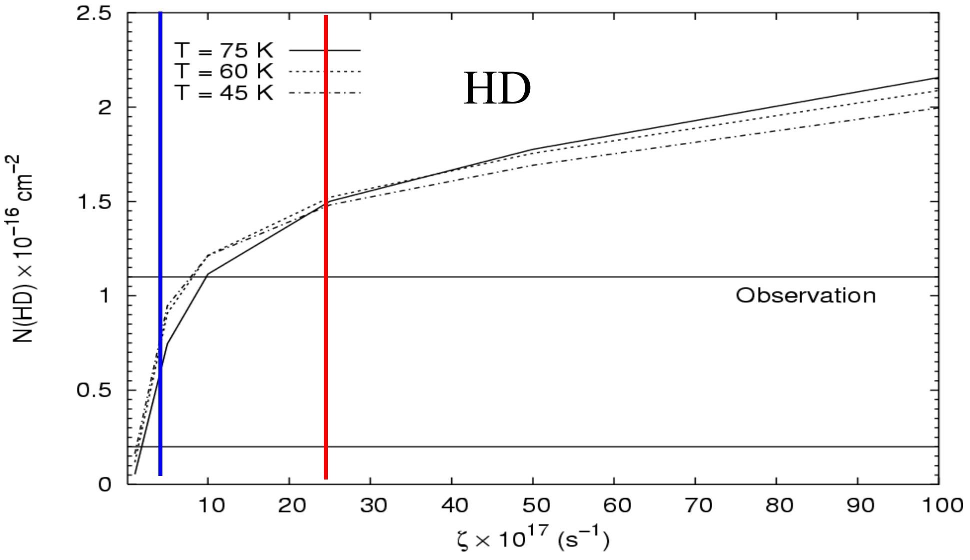
— $\zeta = 5\times10^{-17}\ \mathrm{s}^{-1}$

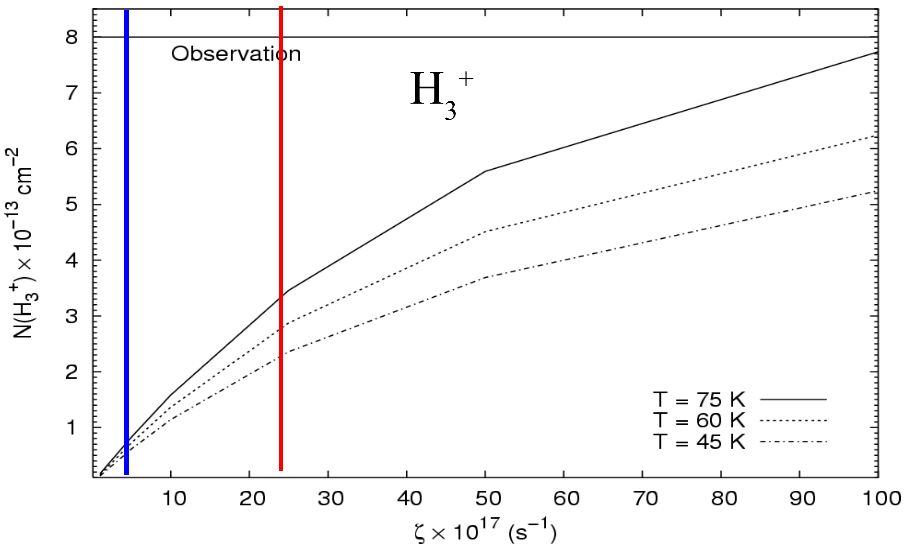
— $\zeta = 25\times10^{-17}\ \mathrm{s}^{-1}$ (Le Petit, Roueff, Herbst 2004)

$\mathrm{O} + \mathrm{H}^+ \longrightarrow \mathrm{O}^+ + \mathrm{H}$ $\quad k = 6\times10^{-10}\exp(-227/T)$

the determination of ζ from N(OH) is highly dependent on T







Conclusion :

- a higher value of ζ is required to explain H_3^+
- but this value cannot be too high or too many electrons are produced

  overestimation of N(C) and N(S)

Model :

2 components : a diffuse one + a dense one (C_2 et C_3)

	Diffuse	Dense	Total	Observations	
H	3.5(20)	1.4(17)	**3.5(20)**	**5.7(20)**	7.1(20)
H_2	4.5(20)	1.1(19)	**4.6(20)**	**3.2(20)**	**7.1(20)**
f			**0.7**	f = **0.53 - 0.66**	
HD	1.5(16)	3.9(13)	**1.5(16)**	2.0(15)	**1.1(16)**
H_3^+	2.9(13)	5.0(09)	2.9(13)	8.0(13)	
C^+	1.6(17)	1.2(15)	1.6(17)	1.8(17)	
C	1.4(15)	1.6(15)	2.8(15)	2.9(15)	3.6(15)
CO	3.5(14)	7.9(13)	4.2(14)	5.4(14)	
CH	2.4(12)	5.6(12)	8.0(12)	1.9(13)	2.0(13)
C_2	1.9(11)	1.9(13)	1.9(13)	1.6(13)	2.2(13)
C_3	3.1(08)	2.1(12)	2.1(12)	1.0(12)	
CN	6.6(10)	1.9(12)	1.9(12)	2.7(12)	3.3(12)
NH	3.5(11)	1.2(09)	3.5(11)	9.0(11)	
O	4.0(17)	7.2(15)	4.0(17)	0.2(18)	1.0(18)
OH	4.9(13)	1.1(09)	4.9(13)	4.0(13)	

<u>Parameters :</u>

$\boldsymbol{\zeta = 25 \times 10^{-17}\ s^{-1}}$

diffuse : $n_H = 100\ cm^{-3}$

$\chi = 2$

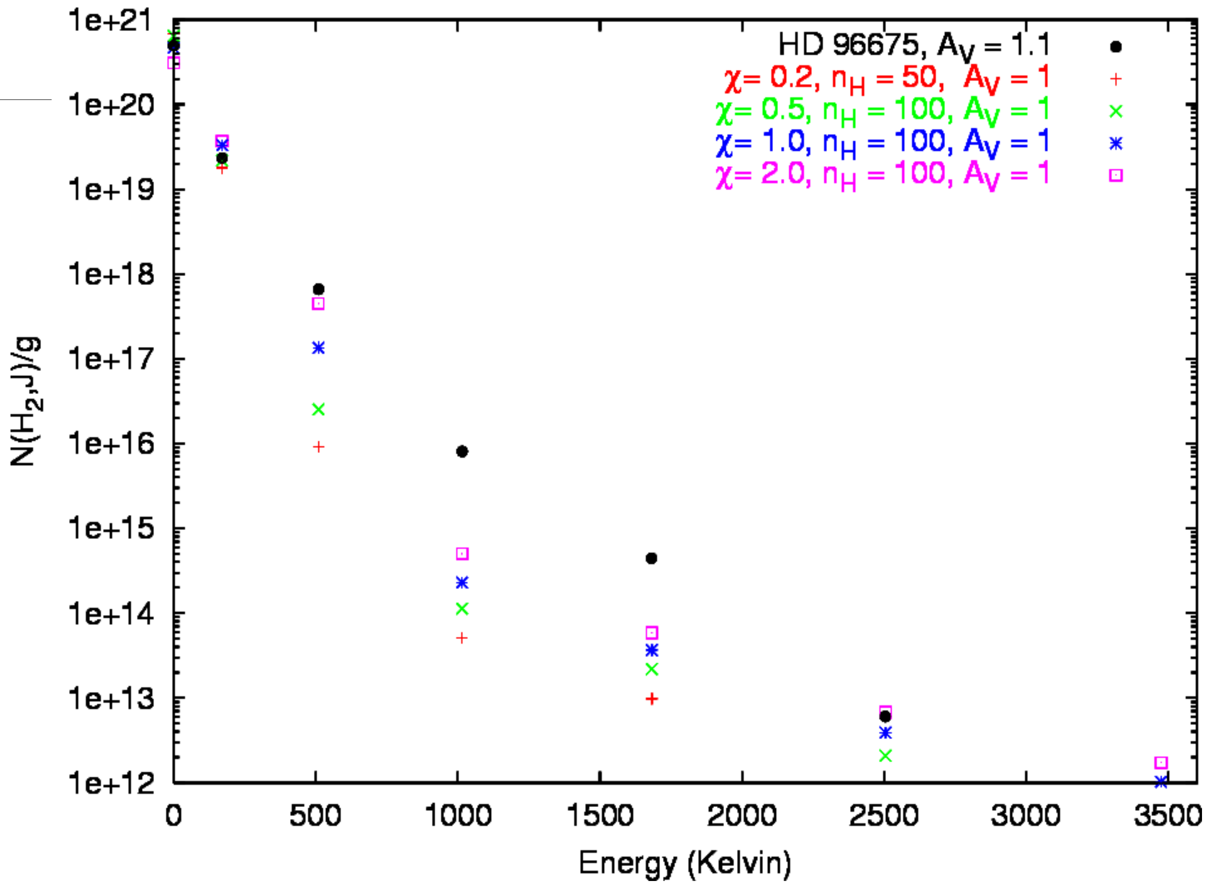
dense : $n_H = 2 \times 10^4\ cm^{-3}$

$\chi = 0.5$

<u>Predictions :</u>

$N(OH^+)$	7.6(11) cm^{-2}
$N(H_2O^+)$	5.5(11) cm^{-2}

H_2 excitation



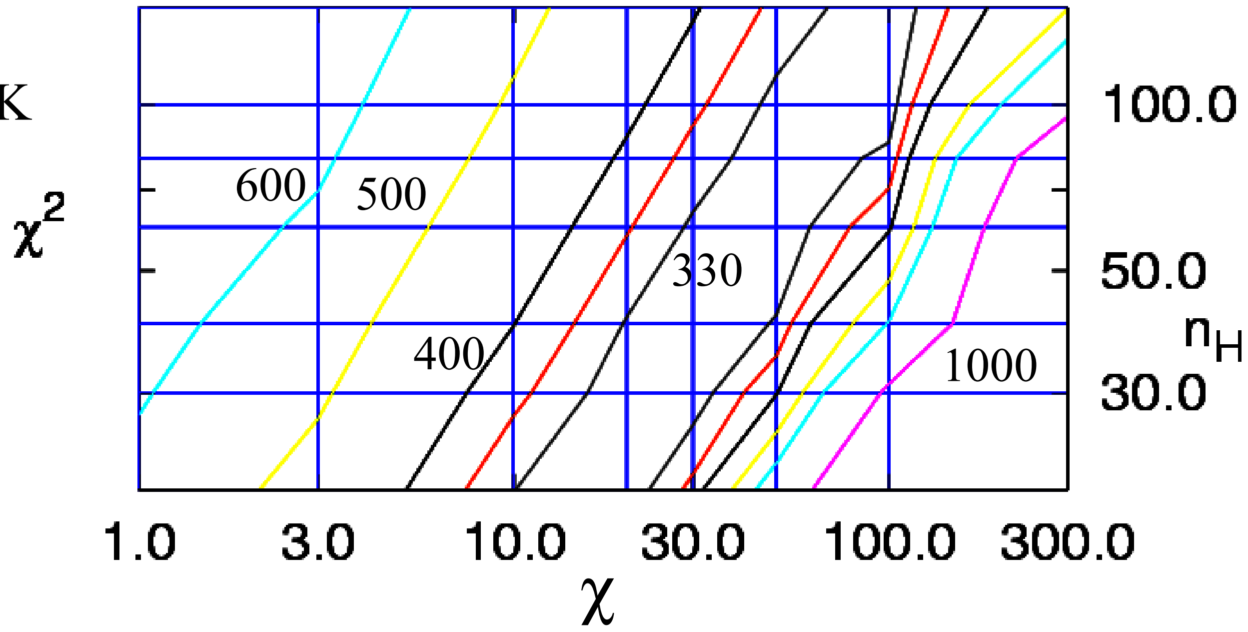
Excepted for some particular lines of sight the excitation of H_2 is not reproduced by UV pumping

The mechanism to transfer the energy from stars and SN remnants to the ISM is not understood !

Other associated problem:

$C^+ + H_2 \longrightarrow CH^+ + H \quad \Delta H = 4500$ K

Chemical models underestimate the observations by a factor 1000



Possible solutions :

- C shocks (G. Pineau de Forêts, D. Flower)
- turbulence (E. Falgarone, K. Joulain)
- collisions with the electrons

Conclusion

- Many observational constraints on many lines of sight
- Models give very good results
- **But the two fundamental questions of the diffuse ISM still remains :**
  - **How to explain the abundance of H_3^+ in the diffuse ISM ?**
    - Problem of the structure of diffuse clouds
    - Problem of the rate of ionization of the diffuse clouds
  - **How the energy from stars and supernovae is transfered to the ISM ?**
    - Which physical mechanism excite the rotational levels of H_2 ?
    - How is formed CH^+ ?

Need for theory !