NEED FOR

HIGH-RESOLUTION
FAR ULTRAVIOLET
SPECTROSCOPY

FOR INTERSTELLAR MEDIUM STUDIES

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Definition

- Far-UV wavelength domain:

  below Ly α, or below $\lambda < 1150$ A

To be covered together with “traditional” UV: 1150 – 3200 A

- High wavelength resolution:

resolving power $R > \lambda/\delta\lambda > 100\,000$

$\Delta v < 3$ km/s

Why a high-resolution, far-UV spectrograph ?

Because it has never been done !

in an observatory-type mission.

Opening this totally new domain

would open a new discovery space

Why a high-resolution, far-UV spectrograph ?

Comparison with past or existing facilities

- Far UV: FUSE (years 1999 – 2007)

$15\,000 \leq R \leq 20\,000$, λ coverage = 907 — 1187 Å, $13 \leq A_{eff} \leq 50$ cm^{-2}

- High resolution: HST STIS Echelle gratings (1997 – 2004 ; 2009 - …)

R = 114 000, λ coverage = 1150 — 3100 Å, $130 \leq A_{eff} \leq 300$ cm^{-2}

- Both far-UV and high resolution : IMAPS:

R ~ 80 000 – 120 000, λ coverage = 950 — 1150 Å, $A_{eff} = 4.5$ cm^{-2}

But only 10 hot stars observed

on ORFEUS-SPAS II deployed for 16-days in 1996 from Space Shuttle

Why a high-resolution, far-UV spectrograph for interstellar studies?

- Why the far-UV:

  The far-UV gives access to a wealth of atomic and molecular lines,

  including key diagnostics --not accessible elsewhere—

  of cold, warm, and hot gas.

- Why high-resolution:

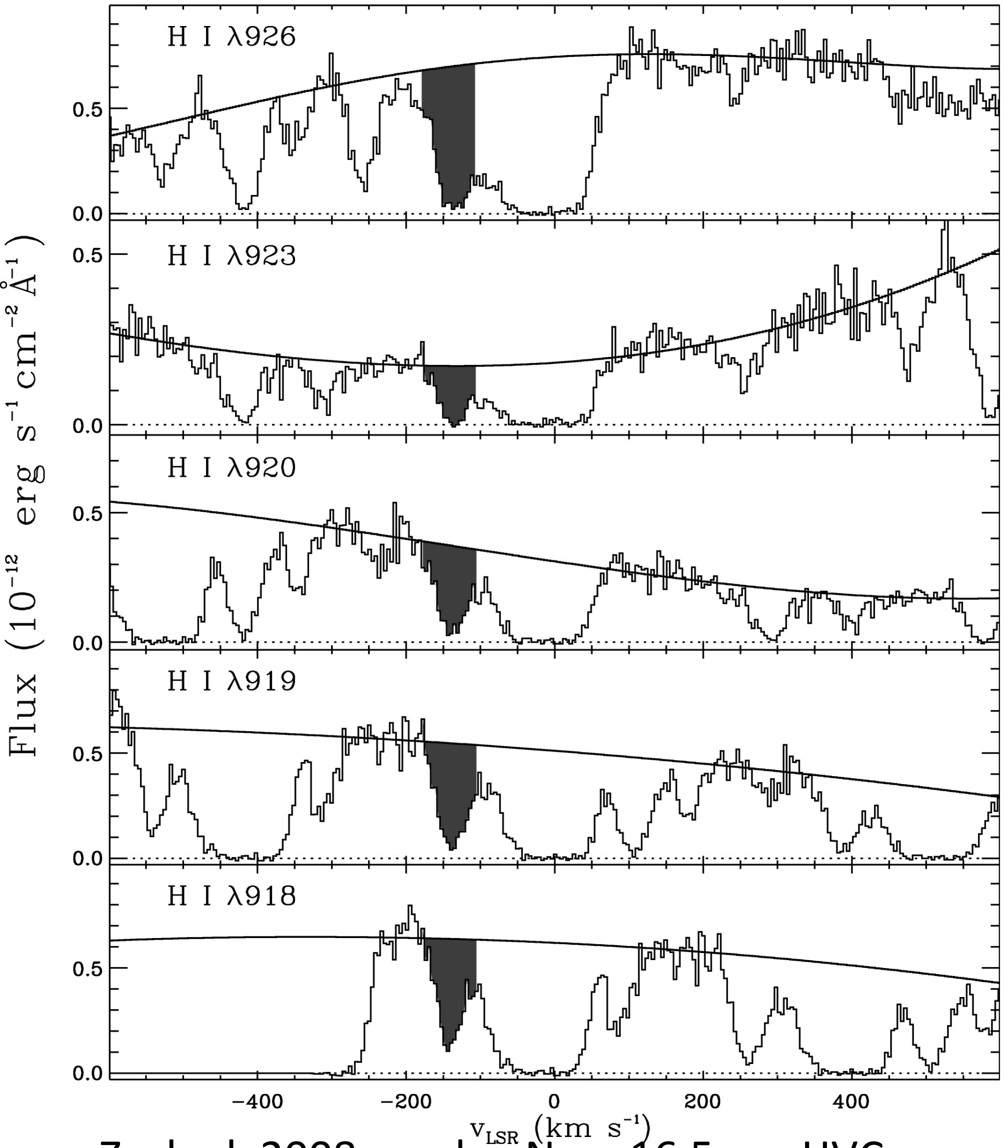
  High resolution allows

  - to resolve velocity components: access to physical characteristics of individual components, not average
  - to get accurate velocity profiles,
  - to resolve molecular bands and compare the different rotational levels,
  - to relate kinematics and gas properties.

1- Why the far-UV:

The far-UV gives access to a wealth of atomic and molecular lines, including key diagnostics --not accessible elsewhere-- of cold, warm, and hot gas.

Why far-UV ?
H I Lyman series 912 A – 1216 A: low HI measurements



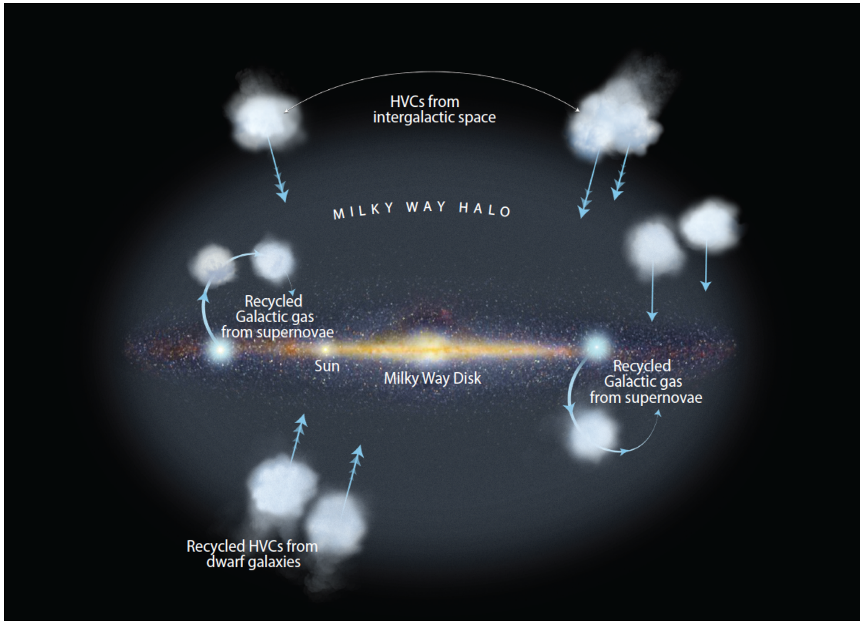
Zech el. 2008 log N_{HI} = 16.5 HVC

- to explore N_{HI} in low N_{HI} regime where it is otherwise extremely difficult/ impossible to observe,

- e.g., low N_{HI} in high velocity clouds in the disk or halo

- GBT can reach log N_{HI} ~ 17.3, but no present or future radio telescope will be able to reach N_{HI} lower than 17 dex

- Without HI, one cannot derive the metallicity of the gas



Why far-UV ?
H I and D I Lyman series: D I measurements

- Validate big-bang nucleosynthesis with observations of Deuterium More favorable in low-metallicity systems at high z (no uncertainty due to D destruction in stars)
- But it is also useful to understand D depletion onto grains (D/H varies in the nearby ISM) by Galactic deuterium measurements
- Measurements of D require to observe Lyman series lines shortward of Ly-beta ($\lambda < 1025$ A)

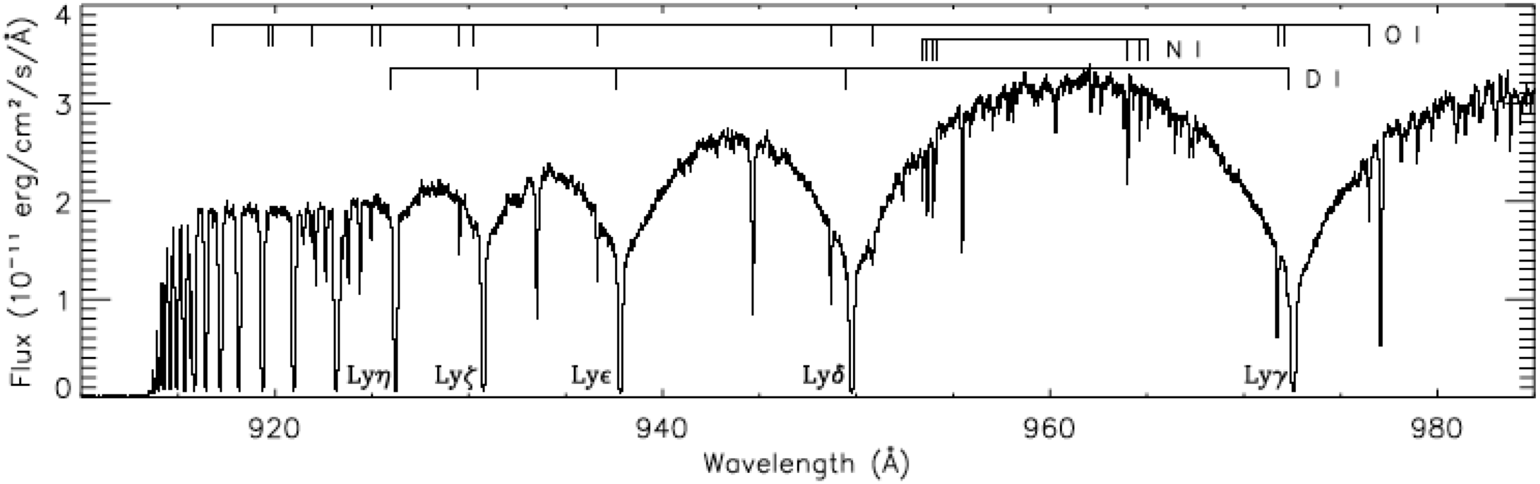
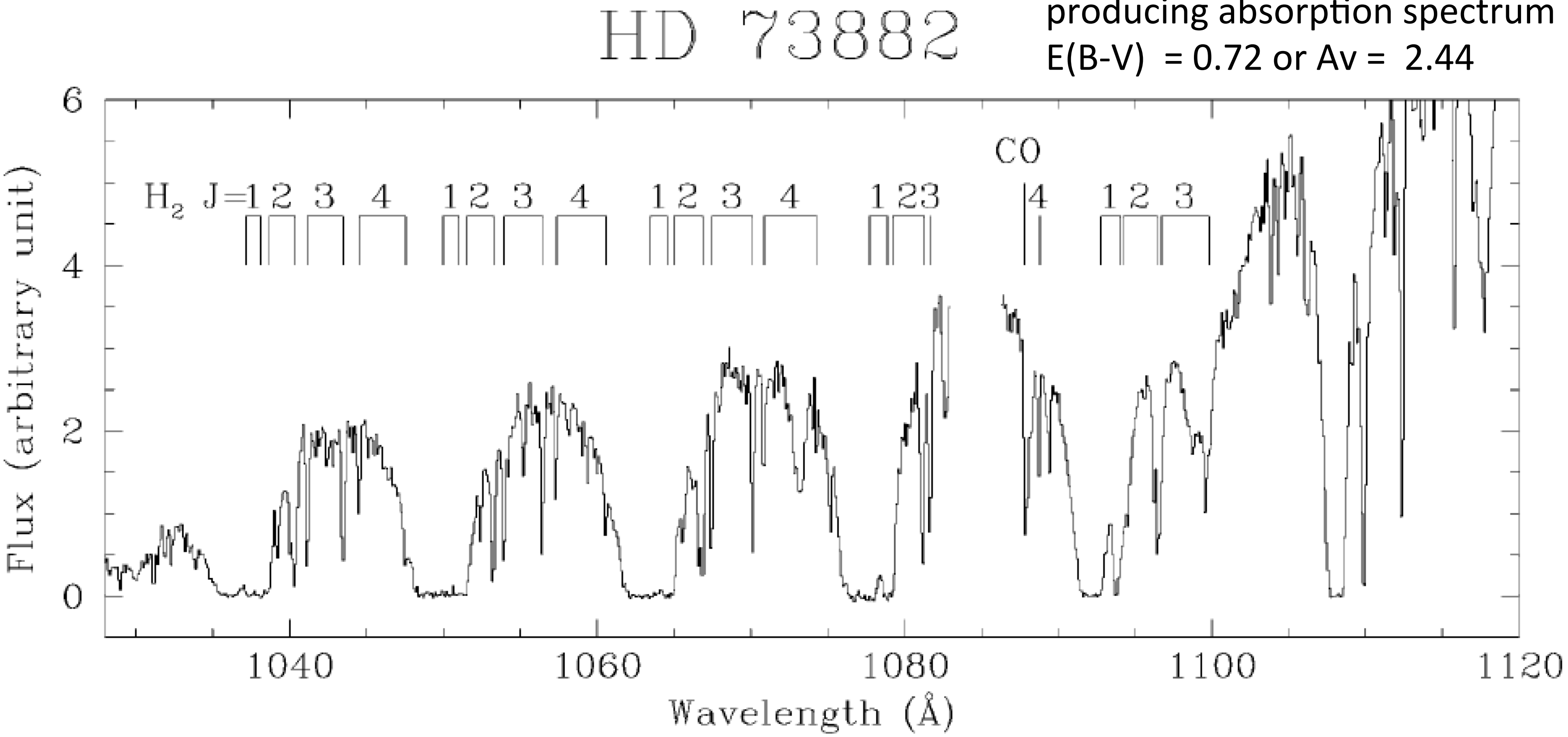


FIG. 2.—*FUSE* SiC1B spectrum of WD 2211−495 (Hebrard et al. 2002)

Why far-UV ?
H2 and CO molecular bands: molecular gas studies

H2: 844 to 1155 A. (5 Lyman bands: 1030 to 1155 A)
CO : 912 to 1455 A and C I: 945 to 1656 A

Star shining through
a translucent cloud
producing absorption spectrum
E(B-V) = 0.72 or Av = 2.44



Why far-UV ?
N II 1084 A: indicator of partly or fully ionized gas.

- Together with N I (1134 A, 1200 A) -> precise ionization ratios
- N is scarcely depleted onto grains -> NI + NII gives total H column density
- It has two excited fine-structure levels that allow us to measure electron densities.
- FUSE had very poor coverage of the N II absorption features near 1085 A.

Example of the use of N II in the alpha Leo sight line (Gry & Jenkins, 2017), d = 24 pc

N(Mg I) /N(Mg II)
+ N(C II*) / N(C II)

- n_e= 0.11 (+0.025, -0.03) cm^{-3}
- T = 6500 (+750, -600) K

N(N I) + N(N II)
+ N depletion
(weak and constant −0.109 ± 0.119 dex)

- $N(H_{tot})$ = 2.8 (+1.2, -0.7) 10^{18} cm^{-2}

$N(N I) / N(N_{tot})$
+ photoionization model
+ all column densities

- $n(H_{tot})$ = 0.30 (+0.10, -0.13) cm^{-3}
- ionization fraction χ = 0.33 (+0.09, -0.06)
- Shielding of external radiation: [4.3-7.0] 10^{17} cm^{-3}
- Depletion level for all species

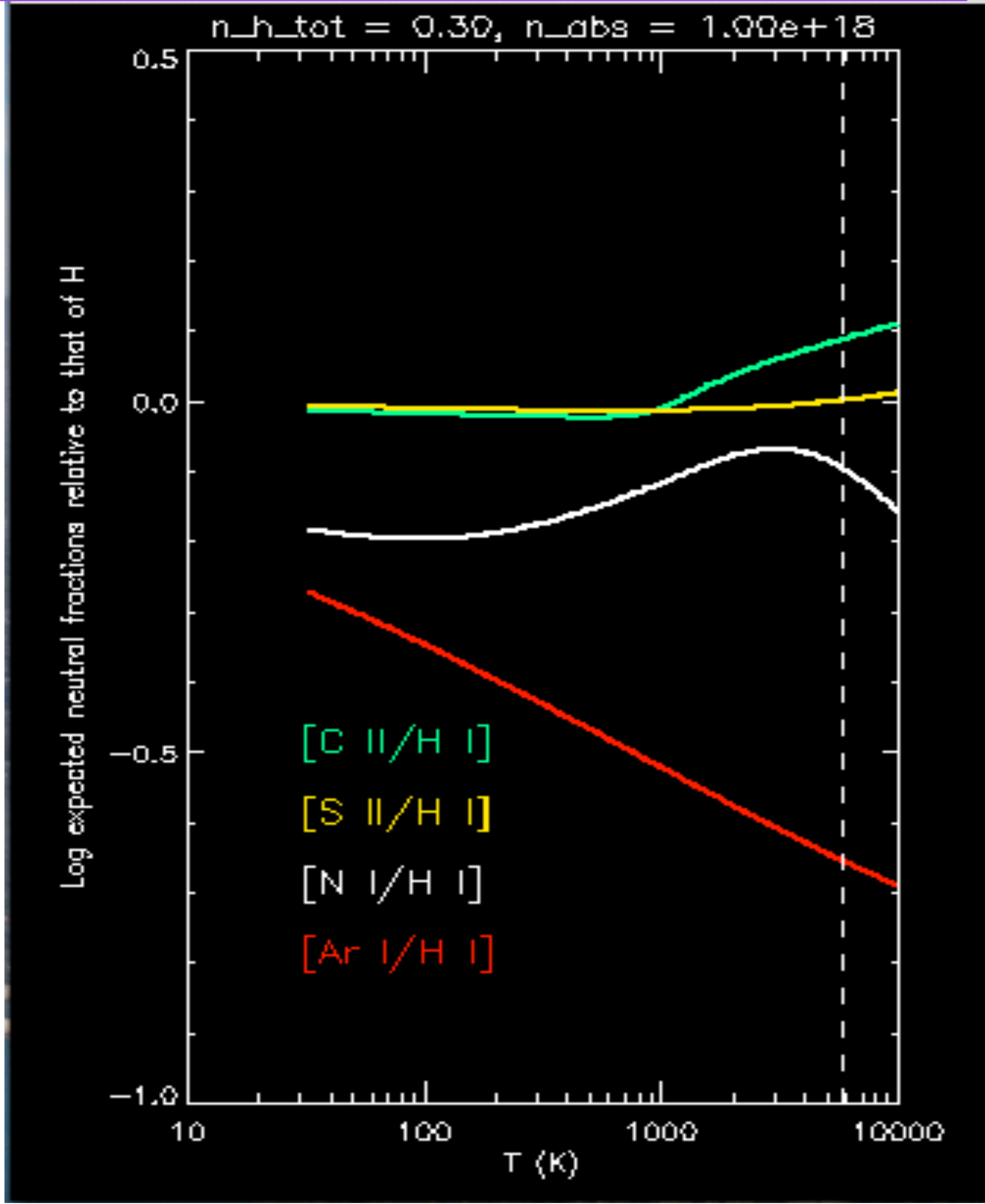
Why Far-UV ?
Ar I (1048 A, 1066 A): partly ionized gas

In a mostly neutral medium exposed to the ambient EUV and soft X-ray ionizing radiation, the argon atoms are far more susceptible to being ionized than hydrogen atoms.

-> Ar I/H I (or its proxy Ar I/O I) gives indication about the degree of ionization and of the strength of the photoionization (Jenkins 2013)

-> which in turns gives indication of neutral and electron densities

Credit: E.B. Jenkins



Why far-UV ?
O VI 1032 A, 1036 A: Highly ionized gas

- OVI is observed ubiquitously in absorption towards stars within the disk and halo of our Galaxy, as well as in a wide range of extragalactic environments
- We still need to understand the source of the O VI features
  - if in collisional ionization equilibrium, gas producing O VI has $T \approx 3\ 10^5$ K, not produced by stellar photoionization
  - do they arise from bulk regions of gas that are maintained at $T = 3\ 10^5$ K ?
  - or from gas that has cooled to much lower temperatures but has not yet had a chance to recombine (the cooling time is much shorter than the recombination time) ?
  - Is O VI seen in turbulent mixing layers or conduction/evaporation interfaces between warm gas and hot (10^6 K) gas ?
- Up to now, all we have been able to do is to compare the abundances of O VI with other highly ionized species and then test them with theoretical models.
- A good understanding of the kinematics of O VI absorption (widths and velocity centroids) would help to understand better the regions that create the features.
  - relate it to lower-ionization species
  - get information on its physical conditions (temperature)

2- Why high-resolution:

To resolve interstellar components:

Need resolution $\Delta v \approx$ FWHM of the lines

$$R = \lambda/\Delta\lambda = c/\mathrm{FWHM}$$

FWHM governed by turbulence, temperature and mass:

$$b^2 = v^2_{turb} + T/60\ m \qquad (\mathrm{FWHM} = b/0.6)$$

2- Why high-resolution:

$$b^2 = v^2_{turb} + T/60\ m$$

The ISM exists in mainly 3 phases:

cold $T \approx 20\text{-}200$ K, warm $T \approx 7000$ K, and hot $T \approx 10^{5\text{-}6}$ K

Typical width values for cold gas:

- Resolve CO or C I with turbulence of 1.5 km/s → FWHM=2.5 km/s→ R≈120 000
- H2 with T≈200 K and v_{turb} ≈1.2 km/s → b≈1.8 km/s → FWHM≈3 → R≈100 000

Typical values for warm gas:

- resolve Fe II with turbulence of 1.4 km/s and T = 6 500 K

→FWHM ~ 3 km/s→ R ~ 100 000

- higher R to resolve lines of lighter elements

Typical values for hot gas:

- O VI at $T=2\ 10^5$ →b=14 km/s → FWHM = 24 km/s →R = 12 500

Why high resolution ?
Resolve velocity components

Illustration: an ideal case of complete UV line sample.

LISM absorption spectrum towards α Leo

V1 = 8.8 km/s   V2 = 14.4 km/s

Full HST STIS spectrum

High resolution R ~ 114 000

(H I, D I) ,C II, C II*, N I, O I, Mg I, Mg II, Al II, Si II, S II, Fe II
(C IV, N V, Al III, Si III, Si IV, S III)

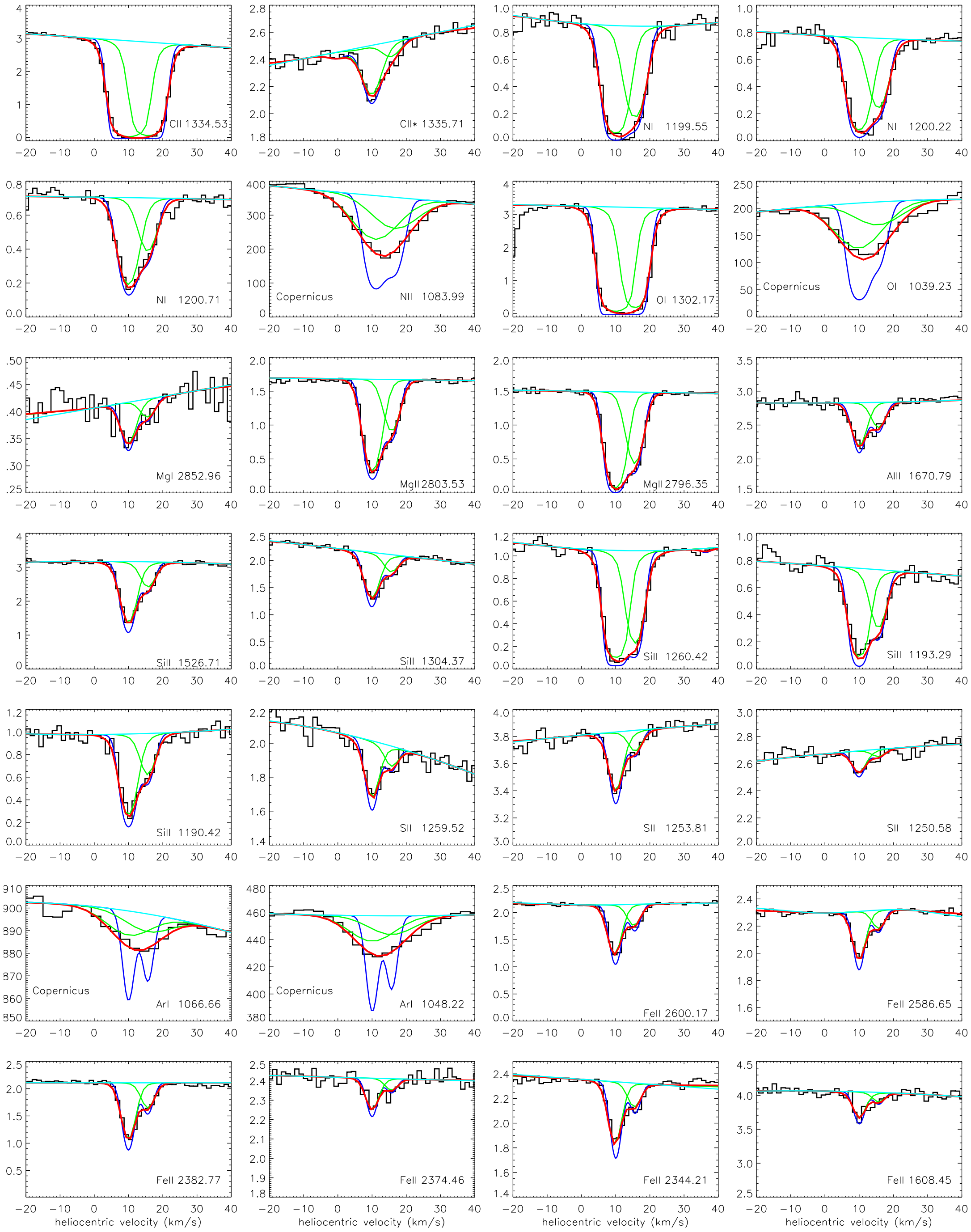
+ unpublished Copernicus spectra

(year 1977) R~ 20 000

for N II(1084A), O I (1039A), Ar I(1048, 1066A)

1- velocity components individualized by STIS with R=100 000 (not by Copernicus) Δv = 5.6km/s

2- Lines almost resolved: lines only slighly distorted by convolution with STIS LSF (unlike for Copernicus)



(Gry & Jenkins 2017)

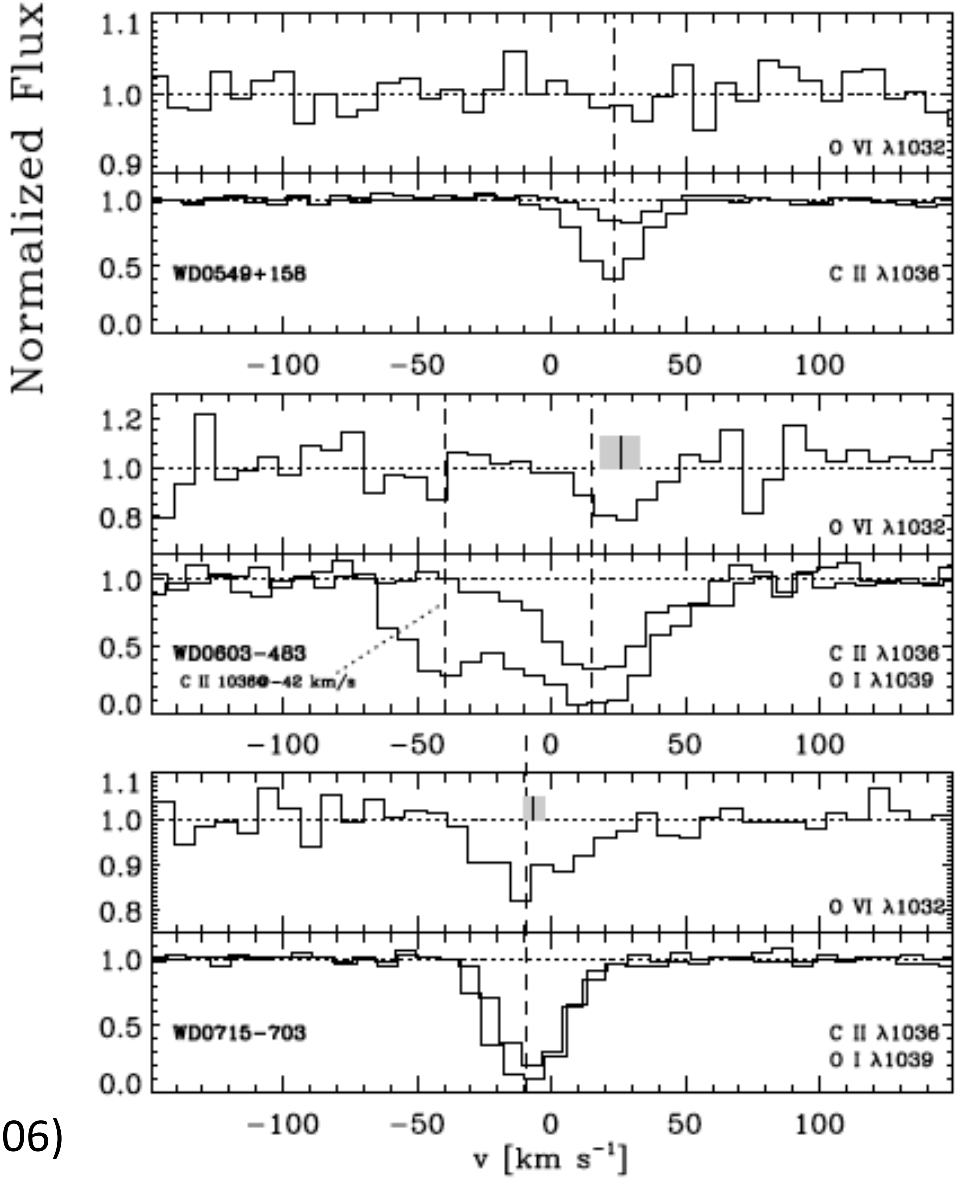
Why high resolution ?
Relate kinematics and gas properties

To address the origin and nature of the O VI gas
(e.g. conductive interface, radiative cooling, turbulent mixing layers),

we need information on its velocity structure: number of components, velocity centroids and line width to

- relate it to lower-ionization species
- get information on its physical conditions (temperature)

FUSE spectra R~ 15 000



Savage & Lehner (2006)

Why high resolution ?
Get accurate velocity profiles

IMAPS data evidence a steady increase in velocity dispersion with rotational excitation level J, associated with a small drift toward more negative velocities detected thanks to R = 110 000 (Jenkins & Peimbert 1997)

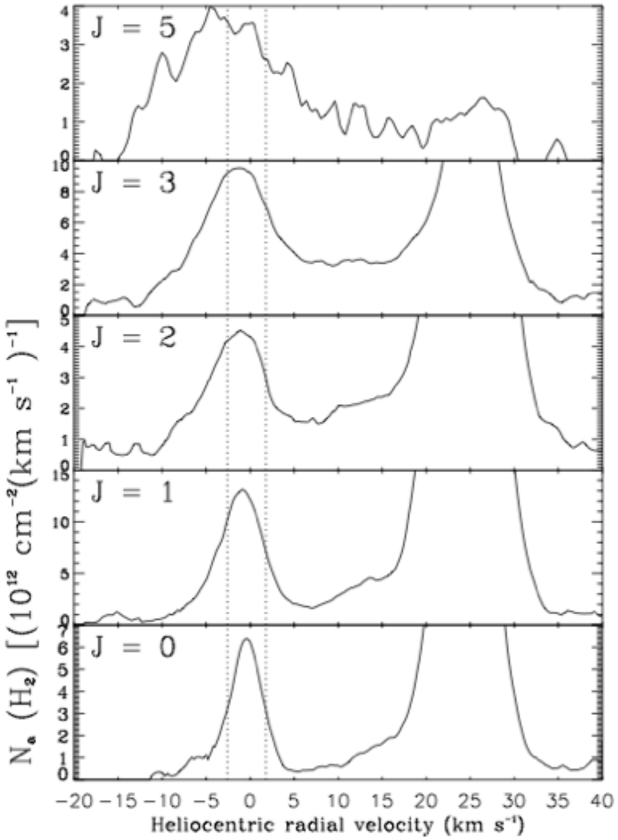
- **H2 created by the shock.**

Jenkins & Peimbert interpret the rotational temperature of 950K as heating due to the passage of a shock. Because of kinematic reasons, they argue that H2 must be formed in the post-shock zone where the density of the gas reaches a level where molecules can be formed. As the post-shock gas cools down at T = 2000 – 10 000K, the gas is still partly ionized and the most efficient way of producing H2 is via the formation of H^- .

- **Warm turbulent layers** in localized regions of molecular clouds (FUSE data, Lacour et al, 2005)

Can we find enough fast H_2 that might explain the endothermic formation of CH+?

- What proportions of the energy of 4.5eV available upon H2 formation are transferred to vibrational and rotational excitation, kinetic motion of the molecules, or in the form of heat for the grain ?

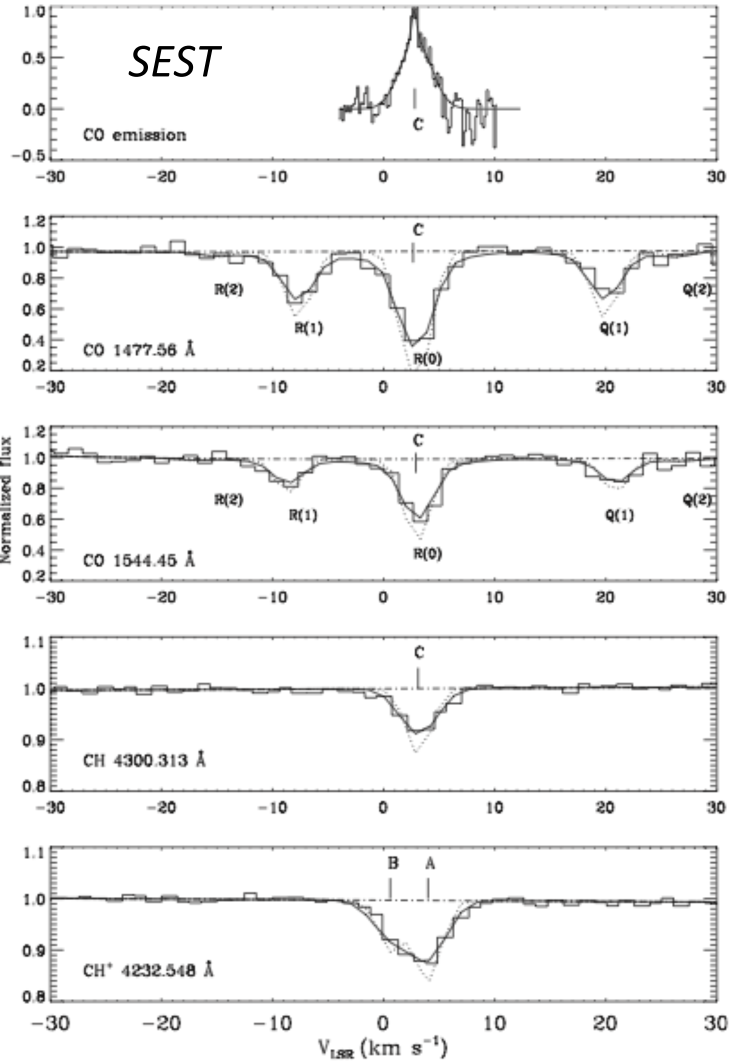


Apparent optical depth ~ column density per unit velocity

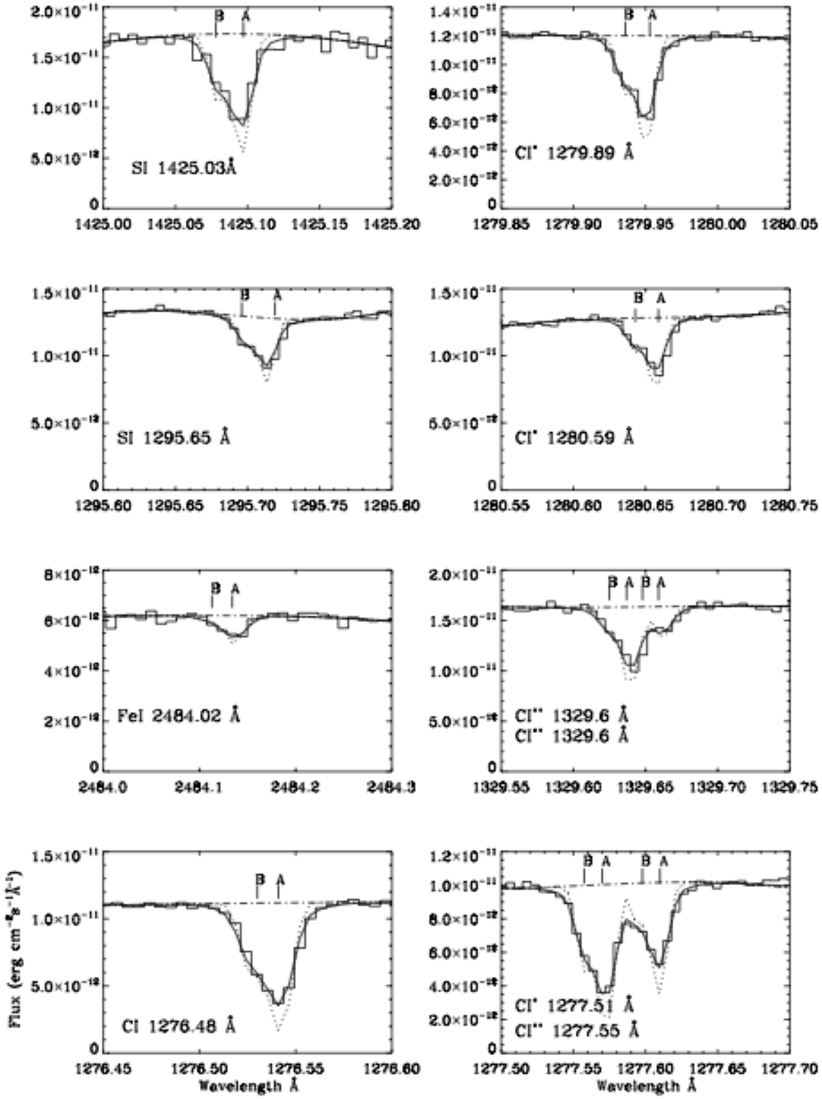
Why high resolution ?
Get internal structure of clouds

evidenced by multi-wavelength high- resolution observations : CO, CH, CH+ and atoms.

Add H_2 !



ission line



Comp A ; B:
3.8 ; 0.4 km/s

Comp C:
2.7 km/s

Line of sight toward HD102065
DC300- in Chamaeleon

From Nehmé, Gry, Boulanger et al (2008): STIS (R ~ 100 000)

Why high resolution ?
Get internal structure of clouds

Most observations (eg H2, CO, CI abundance and excitation) fit with model computations for n ~ 80 cm^{-3}, T~ 80 K, *P/k* ~ 5000 cm^{-3} K in an ISRF of strength G≈ 0.4 x standard Draine's field

BUT :

- Model predicts co-spatial C I, CO and H2 while CI & CH+ and CO & CH show different kinematics
- Model predicts far too low H2 in J>2 level

→ existence of warm H2

→ Need high resolution spectra to see where H2 is: does $H2_{J=0,1}$ follow CO and $H2_{J>2}$ follows CH+ ?

- Excitation of H2 at J>2 is not understood, nor existence of CH+.

→ Shocks or dissipation of turbulence in vortices ?

→ signatures in the velocity distribution of H2 (J)

→ **high resolution needed in H2**

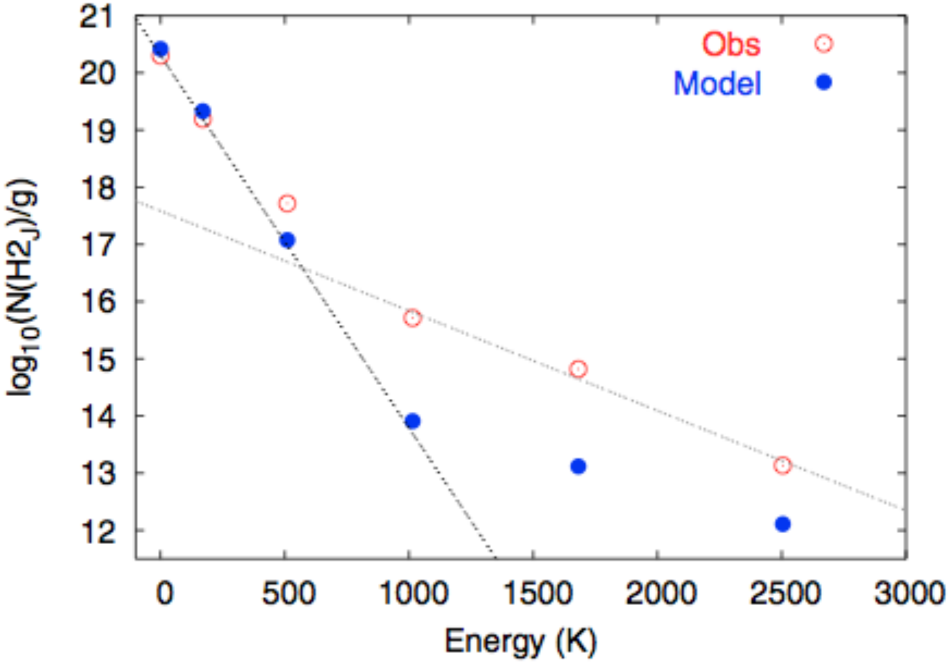
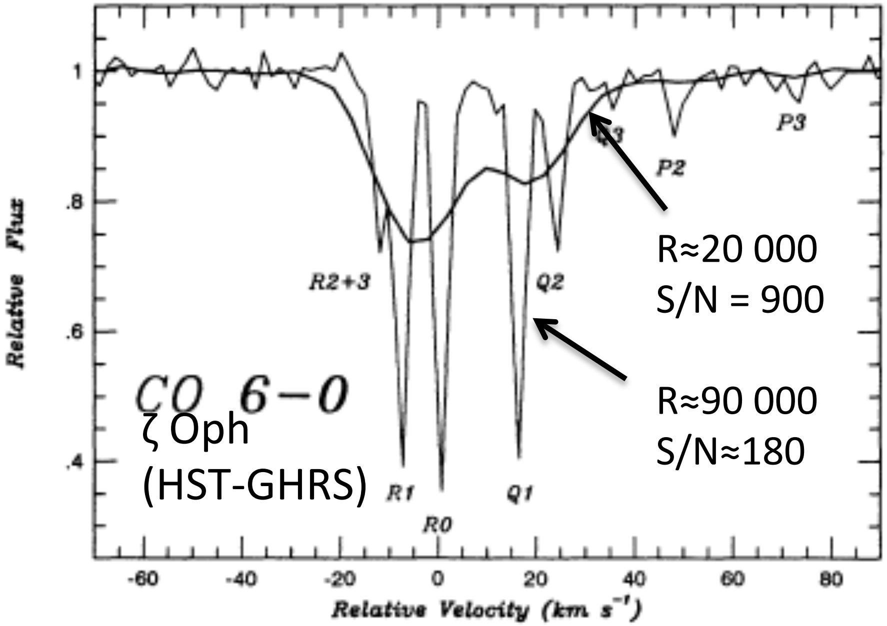


Fig. 9. Observed H$_2$ excitation diagram and reference model. Two excitation temperatures are plotted for $J = 0$ and 1: $T_{ex} = 66$ K, and for $J = 3$ to 5: $T_{ex} = 248$ K.

From Nehmé, Le Bourlot, Boulanger et al (2008)

Why high resolution ?
Resolve molecular bands, compare rotational levels

- High spectral resolution R ≥ 100 000
  - To resolve molecular bands
  - To separate components to study physics and chemistry of individual clouds
  - To resolve individual clouds to get temperatures and turbulence



ζ Oph
(HST-GHRS)

R≈20 000
S/N = 900

R≈90 000
S/N≈180

From Lambert et al (1994)

Summary of ISM requirements for far-UV spectrometer

- **High spectral resolution R ≥ 120 000**
  - Reach a resolution where the individual clouds are resolved to get temperature and turbulence
  - Separate ISM components
- **Full UV and FUV coverage Δλ =** 900 – 3000 A, minimum: **1030 – 1150 A**
  - Molecular gas H2 at high resolution H2: 844 to 1155 A. 5 Lyman bands: 1030 to 1155 A
  - Coupled with CO : 912 to 1455 A and C I: 945 to 1656 A
  - Coupled with [CH, CH+, CN, OH, OH+,DIB carriers]: visible (but can be done from ground)
  - Highly ionized gas: OVI 1032 & 1037 A together with N V, C IV, Si IV, Si III: 1205 to 1550 A
  - H I : Lyman lines: 912 A - 1215 A
  - OI weak lines 920 A
- **High S/N: 100 – 200**
  - Faint lines like Mg I,S II in local cloud: S/N ≥ 200
  - Line profiles→ velocity structure
  - Observe bright targets at high S/N →**detector dynamic to tolerate high count rates**
- **Velocity precision ≤ 0.3 km/s,** minimum: 1km/s
  - Separate velocity components, compare structures of different molecules or ions
- Narrow slit: **0.05 ’’** spatial resolution, spectral resolution, avoid geocoronal emission
- Effective Area:
  - Push to higher A_V in Milky Way. FUSE measured H2 toward $A_V = 1 - 5$ mag (the translucent sight lines) with molecular fractions up to 70% (Rachford et al 2009), but never close to 1. With LUVOIR: observe higher extinction, truly molecular clouds
  - Reach extragalactic targets → Study individual components in ISM in external galaxies

Thank you