Explaining Spatial Profiles of Line Emission in the Horsehead Nebula Using Cloud Surface Curvature

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Photodissociation Regions (PDRs)

Interstellar medium (ISM): gas and dust between stars in galaxies

- $\sim 10\%$ of the total baryonic mass
- main site of star formation

Credit: JWST

PDR: regions of **neutral gas** in the ISM where **far-ultraviolet radiation dominates the chemical and heating processes**

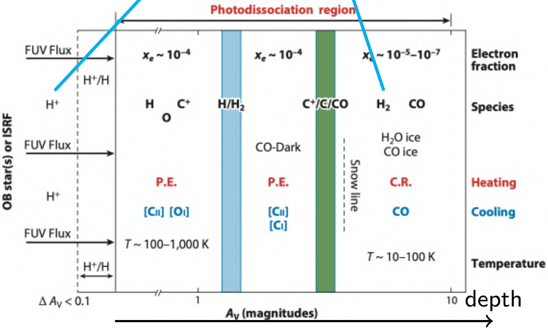
- diagnostic of the ISM
- stellar feedback

Heating: photoelectric effect, cosmic rays

Cooling: line emission

infrared and line emission

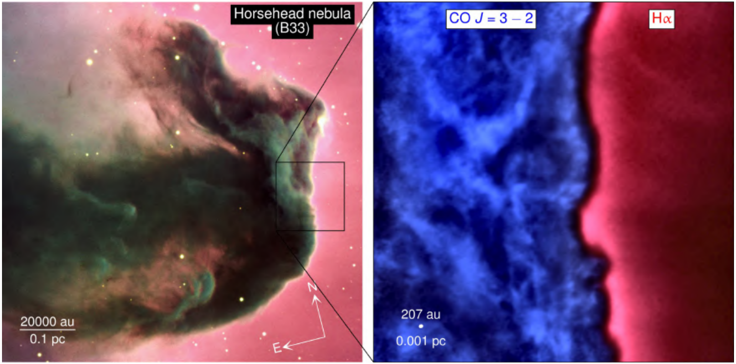
$\Rightarrow$ physical conditions in PDRs



depth

Credit: Tielens 2005

The Horsehead Nebula

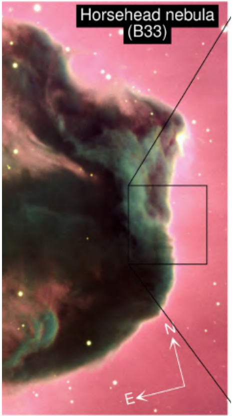


Credit: Hernández-Vera et al. 2023

- observed **edge-on** ⇒ observational access to the chemical stratification

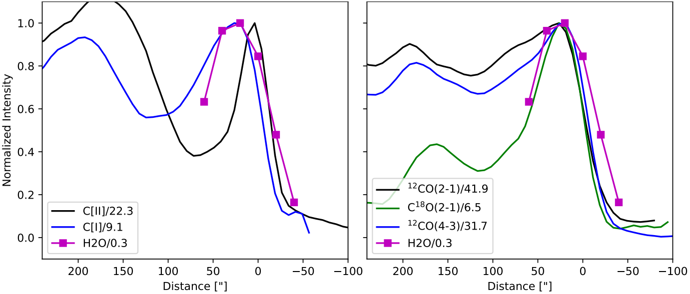
part of a collaboration between JPL, Paris Observatory, IRAM, and CSIC Madrid to study the presence of water in the Horsehead Nebula

Data



observations along a cut through the Horsehead Nebula

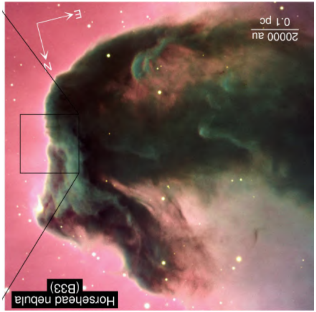
- C^+, C, CO and its isotopologues, and H_2O

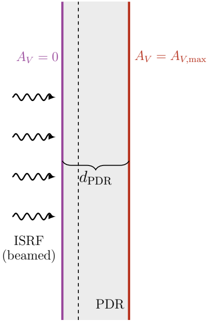


Motivation

1D PDR models

- infinite and uniform in two dimensions, depth-dependent only
  $\Rightarrow$ allows for a detailed study of the physical and chemical processes
- cannot be compared directly to edge-on observations





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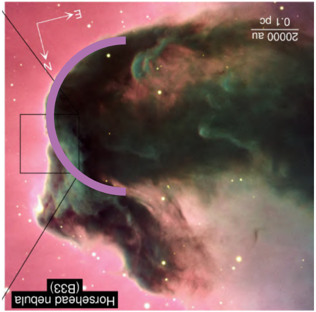
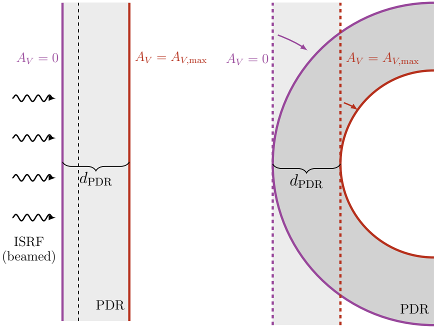
Proposed Solution:

- approximate edge-on regions with **curvature radius**.
- a spherical geometry wrapper for the `MeudonPDR` code





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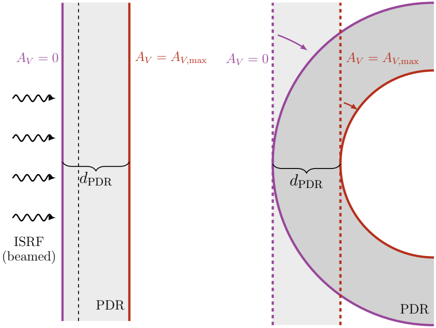
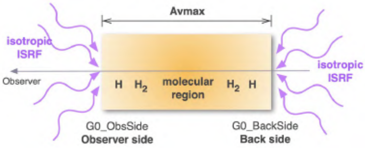
- approximate edge-on regions with **curvature radius**.
- a spherical geometry wrapper for the `MeudonPDR` code
  - spatial profiles of **column densities**
  - solve **radiative transfer** for line intensities
  - **convolution** with the instrument resolution



The MeudonPDR Code

stationary 1D PDR code

- radiative transfer
- chemical balance
- level populations
- thermal balance



Cloud size ($A_{V,\max}$)	40
Proton density (n_H)	$3 \times 10^4 - 3 \times 10^6$ cm^{-3}
Pressure (P)	$1 \times 10^6 - 1 \times 10^7$ K cm^{-3}
ISRF	shape: Mathis, geometry: beam_isot
ISRF scaling factor	$G_0^{\rm obs} = 100,\ G_0^{\rm back} = 0.04$
UV radiative transfer method	FGK approximation, or exact H_2 self- and mutual shielding
Turbulent velocity dispersion	2 km s^{-1}
Extinction Curve	HD38087
$R_V = A_V/E(B-V)$	5.50
$C_D = N_H/E(B-V)$	1.57×10^{22}

[0] Parameter values are based on Maillard, 2023

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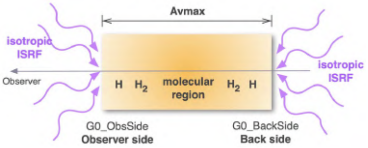

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+ surface chemistry

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From Slab to Spherical Geometry

Input:

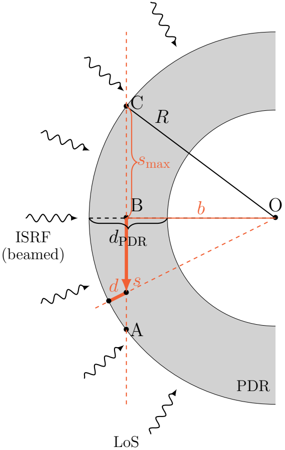
- level number density $n_X(d)$
- cloud radius R (free parameter)
- LoS impact parameter b

Algorithm:

- interpolation of $n_X(d) = f(d)$ to allow computation of n_X at any depth
- $d = R - \sqrt{s^2 + b^2} \Rightarrow n_X(s)$
- integrate along the LoS

$$N_X(b) = 2\int_0^{s_{\max}} n_X(s')\mathrm{d}s'$$

For optically thin lines, $I_\nu \propto N_X$



Convolution with the Instrument Resolution

Algorithm

- interpolate the model grids to uniform ones `x_uniform`, `y_uniform`

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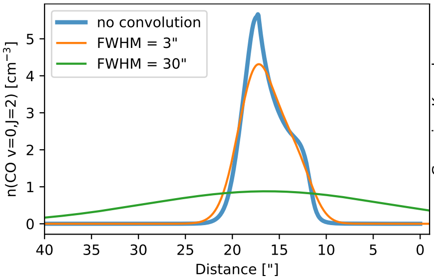
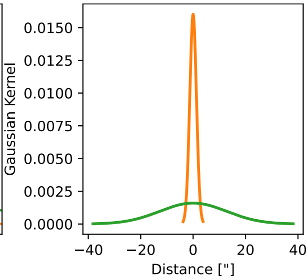
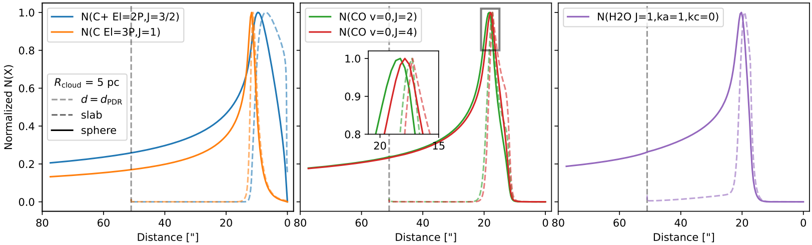
- convolution with truncation at 3σ, padding `y_uniform` with 0





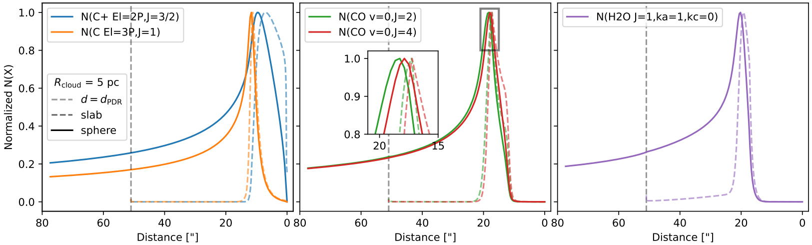
Convolved Column Densities from Spherical Models

step 1: slab vs spherical geometry



Convolved Column Densities from Spherical Models

spherical geometry: the peaks shift to deeper locations within the cloud



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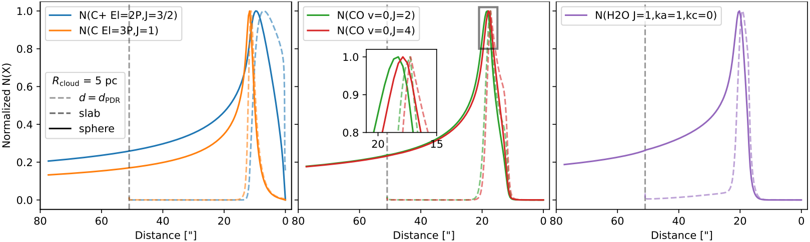
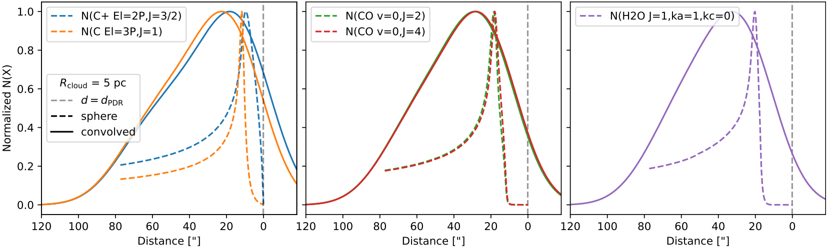


step 2: convolved vs unconvolved column densities



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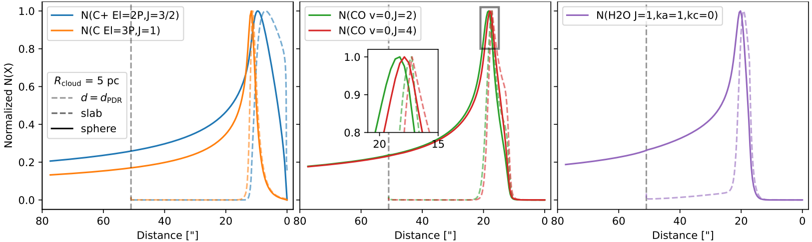
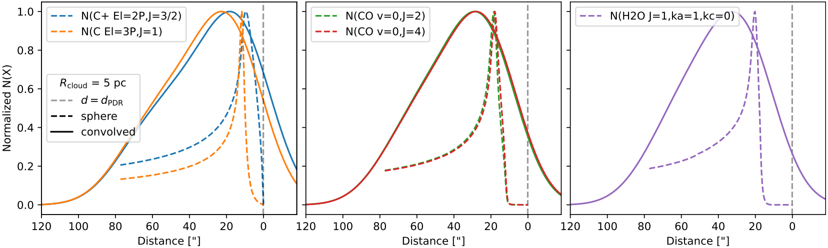
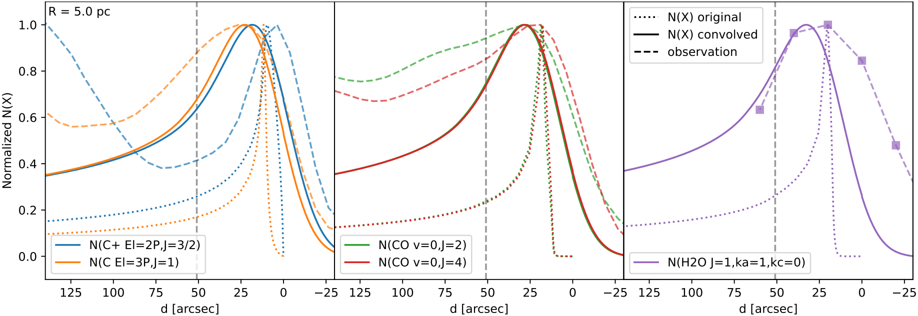


convolution: line spatial profiles are smoothed and further extended



Compare Column Densities with Observations

convolved column densities from **spherical models** match observations better



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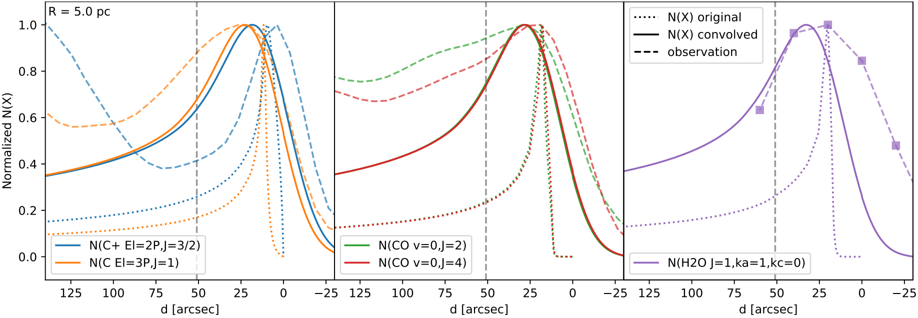

profile width ✓, shape on the front side ✓, shape on the back side ×

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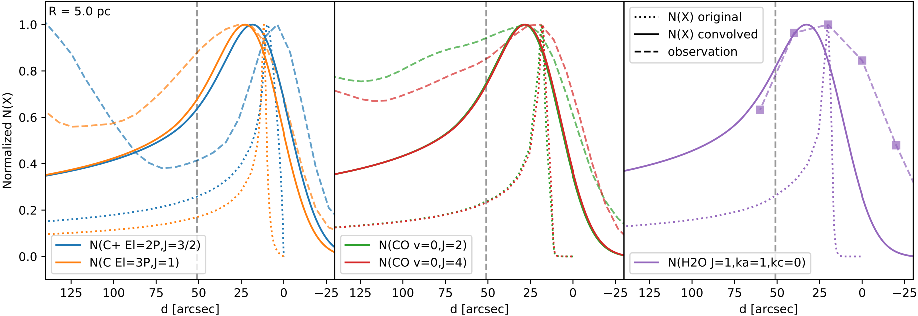

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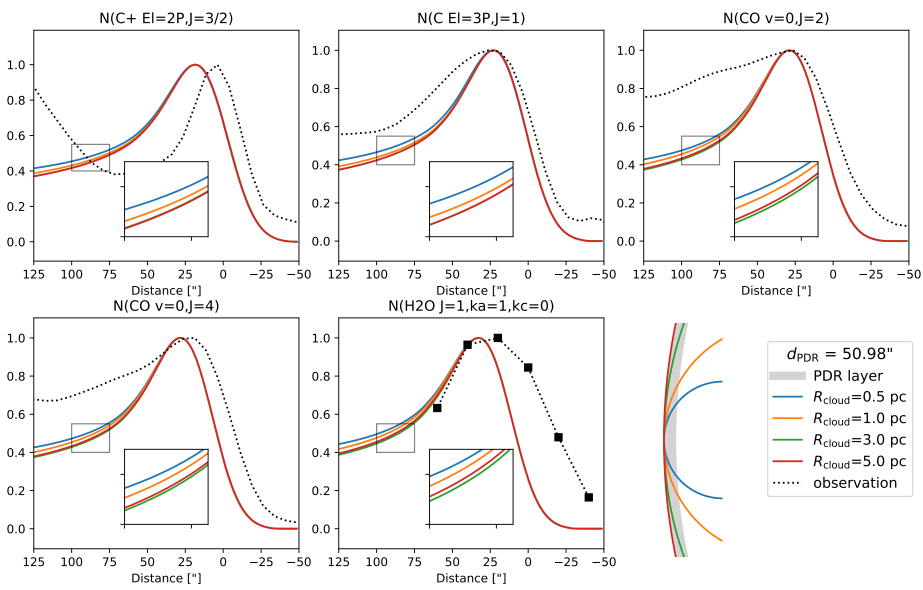
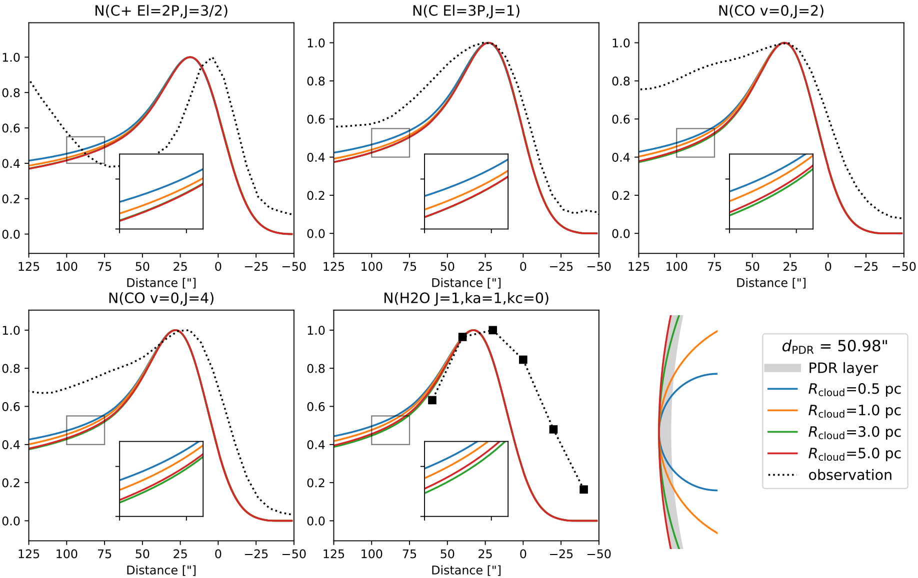
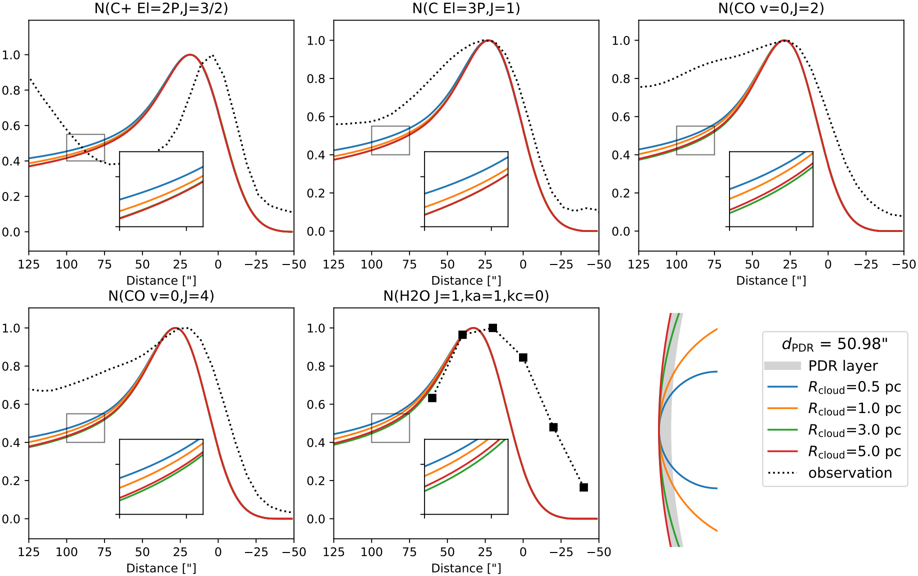
Can cloud radius make a difference?


N(C+ El=2P,J=3/2)
N(C El=3P,J=1)
N(CO v=0,J=2)
N(CO v=0,J=4)
N(H2O J=1,ka=1,kc=0)
Distance ["]
$d_{\rm PDR}$ = 50.98"
PDR layer
$R_{\rm cloud}$=0.5 pc
$R_{\rm cloud}$=1.0 pc
$R_{\rm cloud}$=3.0 pc
$R_{\rm cloud}$=5.0 pc
observation



The differences in column density profiles are trivial



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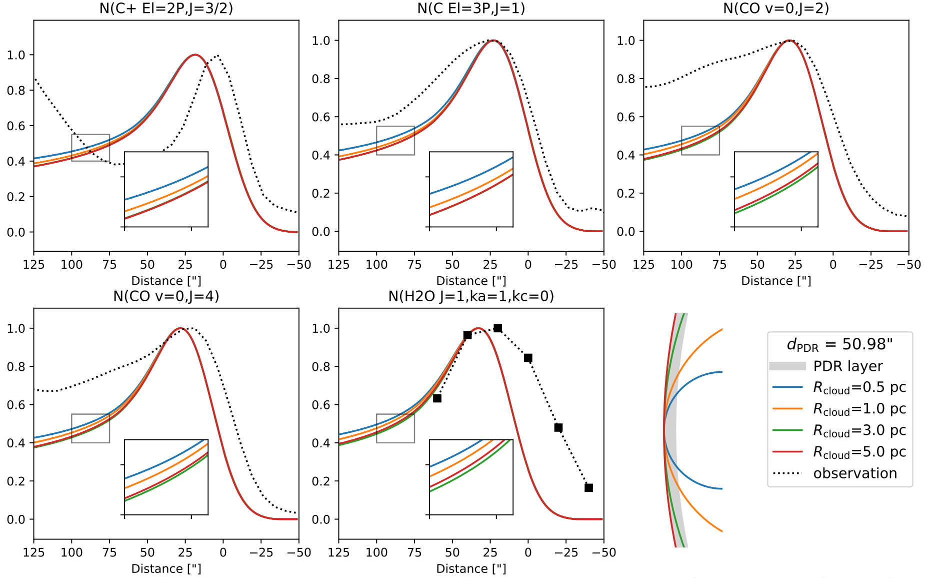
Tail shape $\times, I_\nu \not\propto N_X$?



The differences in column density profiles are trivial $\Rightarrow$ need to solve the radiative transfer equation

Solving the Radiative Transfer Equation along LoS

The radiative transfer equation (neglecting dusts, scattering)

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = A_{ul} n_u \frac{h\nu}{4\pi}\phi(\nu) + B_{ul} n_u \frac{h\nu}{4\pi} I_\nu \phi(\nu) - B_{lu} n_l \frac{h\nu}{4\pi} I_\nu \phi(\nu),$$

with a thermal and turbulent broadening line profile $\phi(\nu)$

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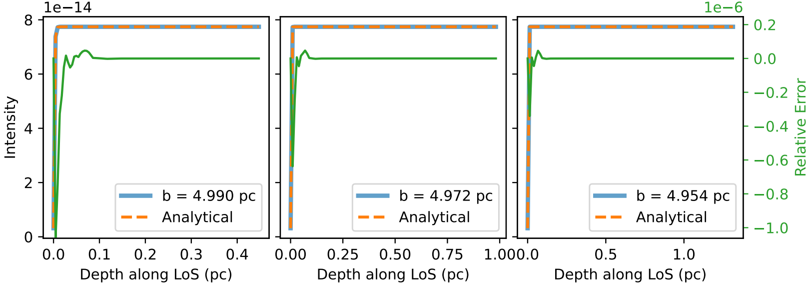
For a toy problem with constant lower and uppper level populations

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = c_1 + c_2 I_\nu, \text{ with } c_1, c_2 \text{ constants}$$



Conclusions

MeudonPDR wrapper

- **column densities in spherical geometry**
- **convolution with the instrument resolution**
- **comparison with observations**

- radiative transfer for line intensities

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  - preliminary results at the line centers

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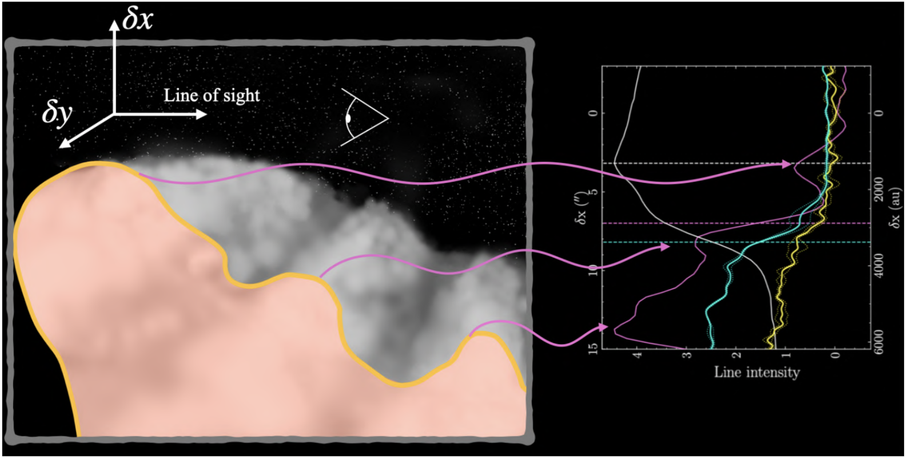
    - solver for the radiative transfer equation
    - preliminary results at the line centers
    - full solution with line broadening

Thank you!

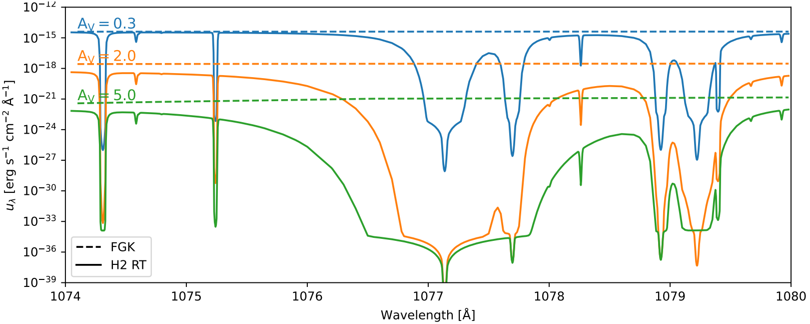
Questions?

Mutiple Peaks in the Observed Profiles



Credit: Maillard, 2023

Exact H2 Self- and Mutual Shielding



Preliminary results of solving RTE at the line centers