The CO ladder in PDRs from HEXOS and WADI observations

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Questions

Relevant for CO-ladder workshop

Energy balance in PDRs:

- distinguish role of UV radiation from shock heating
- gas heating efficiency
- role of different coolants and dust heating and cooling
Example 1: DR21C

- Central HII region
- Collimated outflow to SW, blister to NE
- Ridge in the front
- PDR around HII region and outflow cavities

Marston et al. (2007, Spitzer)

Lane et al. (1990)
DR21C

- Line profiles allow to:
  - Distinguish line intensities from different velocity components
  - Optical depth correction of line intensities
  - Exclude outflow wings and foreground components in PDR model fit

  • ambiguous!

HIFI observations of high-J lines of CO and HCO$^+$ isotopologues
- comparison with ground-based low-J lines
Modeling: KOSMA-τ PDR Code

- Spherical clumps
  → Layering of species and temperature structure as function of UV field

- Recent improvements:
  - Eley-Rideal $H_2$ formation
  - Arbitrary dust properties
  - Full isotopologue network
Modeling: KOSMA-τ PDR Code

- Ensemble of clumps
  - Broadening of excitation ladder

\[ \sum M_i = 1 M_\odot \]

\[ \log \left( \frac{n}{\text{cm}^{-3}} \right) = 4.00, \; \log \left( \frac{\text{Mass}}{M_\odot} \right) = 0.00, \; \log \left( \frac{\chi}{\chi_0} \right) = 2.00 \]
Model for clumpy structure of PDR required

PDR model fit to all lines:

- New HIFI data show two distinct UV fields: $10^5 \chi_D$ and $300 \chi_D$

  → Dense clumps facing the blister outflow
  + clumpy large scale distribution

Lane et al. (1990) + Röllig et al. (2010)
Model for clumpy structure of PDR required

PDR model fit to all lines:

- New HIFI data show two distinct UV fields: $10^5 \chi_D$ and $300 \chi_D$

→ Dense clumps facing the blister outflow + clumpy large scale distribution

No shock component needed!
Example 2: NGC 7023

- Iris nebula
- Focus here on Northern PDR (H$_2$-peak)

Misty (2004)

Spitzer IRAC (Joblin et al. 2008)
Line profiles

Compare 3 data sets:
- HIFI
- CO
  - Gerin et al. (1998)
- $^{13}$CO(1-0) and C$^{18}$O(1-0) from PdBI
  - Pety et al. (2010)

Geometry:
shell-like structure with reabsorption by colder gas
PACS spectroscopy

CO (15-14) line intensity on the Spitzer 8µm map

PACS matrix overlaid on the telescope PSF 75 µm (blue) and 150 µm (red)

Cross-calibration extremely tricky
- Ongoing

Example: CII
- HIFI: $6.0 \times 10^{-3}$ erg/(cm$^2$ s sr)
- PACS: $8.6 \times 10^{-3}$ erg/(cm$^2$ s sr)
Modelling: Meudon PDR code

Version 1.4.3
- Le Bourlot et al. (2012)
- With Eley-Rideal for H\textsubscript{2} formation
- Isobaric: P=3 \(10^6\) K cm\(^{-3}\) fits [CII]
- But: second component needed for molecules/radicals

Diffuse gas:
"atomic" in warm gas (PAH, C+, O)

Dense gas (filaments):
warm molecular gas H\textsubscript{2}, CO,...
NGC7023: PDR code results

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<th>Instrument</th>
<th>Flux [W m⁻² sr⁻¹]</th>
<th>Flux with correction</th>
<th>PDR P=3E6</th>
<th>PDR n=3E5</th>
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- Reasonable fit by two-component model
- But: high-J CO isotopologues still much stronger than predicted
- Problem of plane-parallel setup: stratification not resolvable (A_V=1 → 3'' for 10^5 cm⁻³)
Example 3: The Orion Bar

To be clumpy or not to be clumpy?

FORECAST: 19.7 and 37μm (Shuping et al. 2012)

CO 6-5 (color), $^{13}$CO 3-2 (white contours), OI 1.32μm (red), $H_2$ v=1-0 S(1) (black), $H^{13}$CN 1-0 (blue) (Lis & Schilke 2003)

HIFI central position: 5h35m20.81s -5d25m17.1s
Orion Bar

Full HIFI spectral scan:

- CO excitation flat up to J=15
- Excitation increasing in energy
- Turn over around 700K
- PACS detection up to J=22

Integrated HIFI line intensities for CO isotopologues and CI,CII:

Top: in integrated intensities vs. frequency

Bottom: radiated energy vs. excitation energy
Orion Bar

Full HIFI spectral scan:

- Lines Gaussian, but:
  - Line width strong function of J
  - also for optically thin species
  - Larson-like dependence (?)
  - Contradiction to normal modelling approach

Top: integrated HIFI line intensities for CO isotopologues and Cl, CII

Bottom: Corresponding measured line width
Spatial structure

- Very smooth distribution
Problem:
- negative continuum flux in some spaxels at long wavelengths
- likely due to emission in 1 of the 2 reference positions.
Dominated by [CII] and [OI]

PACS SED Scan
CO excitation

PACS (central + mean; HEXOS) + SPIRE (21" + convolved 42", SAG 4):

$^{12}$CO: Green: Measured
   Blue and red: With opacity correction

$^{13}$CO: Blue: Measured
   Red: With opacity correction
Modelling: Meudon PDR code

Fit of CO excitation temperature by isobaric model:

- For \( E_{\text{up}} > 500 \text{K} \) : \( T_{\text{ex}}(\text{CO}) \) is independent of the radiation field
- Abundance and column density depend on the radiation field
- Low-J CO \( (E_{\text{up}} < 300 \text{K}) \) overpredicted

\[ P = 2 \times 10^8 \text{ K cm}^{-3}, A_v = 5 \]
Comparison to NGC7023

Orion Bar:
- Spitzer (Pilleri et al. 2011):
  - $N_H = 1.1 \times 10^{22} \text{ cm}^{-2} \leftarrow A_V = 6.1 \text{ mag}$
- Herschel:
  - [CII]: $8.5 \times 10^{-6} \text{ W m}^{-2} \text{ sr}^{-1}$
  - high-J CO: $T_{ex} = 140 \text{ K}, N = 4 \times 10^{17} \text{ cm}^{-2}$

NGC 7023:
- Spitzer:
  - $N_H = 2.0 \times 10^{22} \text{ cm}^{-2} \leftarrow A_V = 11.3 \text{ mag}$
- Herschel:
  - [CII]: $8.6 \times 10^{-7} \text{ W m}^{-2} \text{ sr}^{-1}$
  - high-J CO: $T_{ex} \sim 110 \text{ K}, N = 6 \times 10^{16} \text{ cm}^{-2}$
Modeling: KOSMA-$\tau$ PDR Code

Based on Orion Bar picture from Hogerheijde et al. (1995):

H II region

thermal radiocont. vibrational $\text{H}_2$ molecules

background molecular cloud

0.05 pc

0.6 pc

Trapezium Stars

$\Delta \alpha = -20$

$\Delta \alpha = 0$

$\Delta \alpha = 20$

$\Delta \alpha = 40$

$\Delta \alpha = 60$
Modeling: KOSMA-τ PDR Code

2-Component clumpy model

- assume stratification of 2 clumpy layers
- deeper layer sees weaker FUV field due to attenuation
- neglect mutual shielding and shadowing

yellow: closer to the FUV source
beige: further away from the FUV source
Modeling: KOSMA-\(\tau\) PDR Code

2-Component clumpy model:

- Diffuse:
  - \(n = 2.7 \times 10^4\) cm\(^{-3}\)
  - \(\chi = 3 \times 10^4\)
- Dense:
  - \(n = 7 \times 10^6\) cm\(^{-3}\)
  - \(\chi = 2000\)

- model mass: \(0.26\, M_\odot\)

\(\rightarrow\) matches observed col. density of \(6.5 \times 10^{22}\) cm\(^{-2}\) on \((9.6''\)^2\) pixel

Result:

- \(^{12}\)CO lines fitted up to \(J=15-14\), \(J>20\) overpredicted, \(^{13}\)CO well reproduced
- fine structure lines reproduced ([OI] 63\(\mu m\) overestimated due to opt. thick.)
Summary

- High-J CO excited in all three PDRs in spite of moderate average gas temperatures.
  - Explained by enhanced $\text{H}_2$ formation rates at high temperatures through Eley-Rideal mechanism
- Still no comprehensive fit to full CO ladder and spatial stratification structure
- Combination of multiple density components needed
  - Nature of dense component?
    - Filaments vs clumps?
    - Small dense components must be transient
      - Evaporating?
      - How many of these structures are needed?
Summary

• PDR model fits

  – Major progress made thanks to NGC7023 and Orion Bar
  – Need for a two component model:
    • diffuse gas traced by PAH and C+
    • dense component for warm molecular emission (CO, OH, H$_2$, ...)
  – need to form H$_2$ in the warm layers (Eley-Rideal mechanism)
  – still challenging to get a good fit for CO ($T_{ex}$ and N)
  – difficulties on the description of geometry and local physical conditions.
    • predicted transitions on too small scales
      → no stratification would not be observable
  – dense components: → better use KOSMA-τ approach
Summary

But:

- Fits to integrated line intensities miss all the information contained in the line profiles!
  - Assumption of equal line profiles for optically thin tracers is wrong!
  - Self-absorption, outflow wings, turbulence, advection flows, pressure gradients

- More sophisticated models needed
- Modelling/interpretation has only started