The Horsehead Mane PDR

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and

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Why PDRs are important? I. PDRs are everywhere

• Definition:
  – Photon-Dominated Regions or Photon-Dissociation Regions.
  – Far-UV illuminated: radiation with $6 < E < 13.6 \text{ eV}$
    $\Rightarrow$ Radiation can’t ionize H atoms but it ionizes atoms with $E_p < 13.6 \text{ eV}$ (C, Si, S, Fe) and it dissociates and ionizes molecules.
  – Physics and chemistry dominated by the UV radiation field.

• Examples (see “PDR everywhere” Ossenkopf 2007).
  – Protoplanetary disk surfaces.
  – AGB circumstellar envelopes and Planetary Nebulae.
  – Interface between HII regions and dense molecular clouds, e.g. star-forming regions (Orion bar, NGC 2023, NGC 2024, NGC 7023, S106, S140, IC63, Carina, Monoceros, ...).
  – Diffuse or translucent clouds of local ISM.

All these sources also emit in local and high-z galaxies
$\Rightarrow$ understanding them in our Galaxy sheds light on the distant universe.
Why PDRs are important? II. Possibility to accurately test chemistry.

- Complex gas phase chemistry *(hundred of species, thousand of reactions).*

- “Cold” and “diluted” gas. ⇒ **Difficult Theoretical/Experimental efforts.**
  ⇒ **Impossible to get reliable chemical rates for thousands of reactions.**

- Recent attempts to identify a few key chemical reactions in **well-studied astrophysical cases** *(Wakelam et al. 2004, 2006).*

- All “small” ISM molecules are detectable in PDRs.

  ⇒ **A few in-depth observational studies of PDRs can help to set up reliable chemical networks.**
Why PDRs are important? II.1 Possibility to accurately test physics.

- PDR models need special treatment of:
  - Gas phase chemistry (see previous slide).
  - Heating (photoelectric effect) and cooling (FIR/submm radiative transfer).
  - UV radiative transfer, \textit{i.e.} dust attenuation and line self-shielding (basically H$_2$ and CO).

- History:
  - 30 years of development.
  - $\sim$ 10 independent codes with different goals, \textit{i.e.} approximations.
  - Same qualitative trends but large quantitative differences.
    \Rightarrow Additional difficulty to unambiguously interpret the data from ALMA and Herschel.
    \Rightarrow Large benchmarking effort since a few years.
Why PDRs are important? **II.2 Possibility to accurately test physics.**

http://www.ph1.uni-koeln.de/pdr-comparison/intro1.htm

Röllig et al. 2007.

Before the Leiden Workshop

After the Leiden Workshop

Model F1: $n_H = 10^3 \text{ cm}^{-3}$, $X = 10$, $T = 50 \text{ K}$

- Better understanding of the causes of the differences on “simple” test cases.
- Standard are implemented $\Rightarrow$ PDR models are converging but where?
- Conclusion: Need of reliable molecular abundances in some simple sources that can serve as basic references.

The Horsehead Mane PDR

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Horsehead:
One of the most famous object of the sky

ESO VLT:

Hubble Heritage:

But also a fantastic PDR laboratory.

The Horsehead Mane PDR

J. Pety, 2009
Horsehead mane geography:
I. The hunter constellation
Horsehead mane geography:
II. From the hunter constellation to the Orion Giant Molecular Cloud

⇒ $D \sim 400 - 450$ pc ($1'' \leftrightarrow 0.002$ pc).
Horsehead mane geography:

III. From the Orion Giant Molecular Cloud to the IC434 nebula
Orion bar and Horsehead mane geography:
IV. From the IC 434 nebula to the PDR region

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The Horsehead ID card: I. The environment from Bell labs $^{12}\text{CO}$ (J=1–0) wide-field map

- Exciting star: $\sigma$Ori (O9.5V) at $0.5^\circ$ (3.5 pc), PA $76^\circ$. $\zeta$Ori probably shadowed (Philipp et al. 2006).
- Far–UV intensity: $G_0 = 100$ (Habing) or $\chi = 60$ (Draine).
The Horsehead ID card: II. The global structure

KPNO $\text{H}\alpha + \text{BIMA} \, ^{12}\text{CO} \, (J=1-0)$ (Pound et al. 2003)

$\Rightarrow$ Typical pillar \begin{itemize}
  \item Formed in $\sim 0.5$ Myr;
  \item Lifetime $\sim 5$ Myr.
\end{itemize}
The Horsehead ID card: III. Geometry

ISO 7 μm continuum (Abergel et al. 2003)

Filament width ⇒ Edge-on structure, star in the plane-of-sky.
The Horsehead ID card: IV. Kinematics

IRAM/30m $^{18}$O (J=2–1) (Hily-Blant et al. 2005)

Neck in $\sim$ solid rotation (period $\sim$ 4 Myr).

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The Horsehead ID card: V. Condensations

JCMT $850 \mu m$ and $450 \mu m$ continuum (Ward-Thompson et al. 2006)

$\Rightarrow$ 1. East: $4 M_\odot$ in $0.15 \times 0.07$ pc, in gravitational viral equilibrium.

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The Horsehead ID card: V. Condensations

JCMT 850 $\mu$m and 450 $\mu$m continuum (Ward-Thompson et al. 2006)

$\Rightarrow$ 2. West: $2 \, M_\odot$ in $0.31 \times 0.13$ pc;

Dynamics dominated by the ionisation front.

The Horsehead Mane PDR

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The Horsehead ID card: VI. Summary

- KPNO Hα + BIMA $^{12}$CO (J=1–0) (Pound et al. 2003) ⇒ Typical pillar;
- ISO 7 µm continuum (Abergel et al. 2003) ⇒ Edge-on structure, star in plane-of-sky;
- IRAM/30m C\textsubscript{18}O (J=2–1) (Hily-Blant et al. 2005) ⇒ Neck in solid rotation;
- JCMT 850 µm and 450 µm continuum (Ward-Thompson et al. 2006) ⇒ West condensation (2 M⊙ in 0.31 × 0.13 pc) dynamics dominated by the ionisation front.
The Horsehead PDR ID card: I. Coordinate System

Transformations:
- $14^\circ$ counter-clockwise rotation.
- $20''$ translation.

All the following images will be in this coordinate system, adapted to the comparison with models.
The Horsehead PDR ID card: II. Field-of-view vs resolution

- Radioastronomy dilemma:
  Single dish large field-of-view vs interferometer high angular resolution.

- Elliptic field-of-view at interferometer:
  \[ I_{\text{obs}} = B_{\text{prim}} \cdot I_{\text{sky}} + N \Rightarrow I_{\text{cor}} = I_{\text{obs}}/B_{\text{prim}} = I_{\text{sky}} + N/B_{\text{prim}}. \]
  \( \Rightarrow \) Noise increases sharply at the edges and truncation
Radioastronomy dilemma:
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Elliptic field-of-view at interferometer:

\[ I_{\text{obs}} = B_{\text{prim}} \cdot I_{\text{sky}} + N \Rightarrow I_{\text{cor}} = \frac{I_{\text{obs}}}{B_{\text{prim}}} = I_{\text{sky}} + \frac{N}{B_{\text{prim}}}. \]

⇒ Noise increases sharply at the edges and truncation
The Horsehead mane ID card: III.1 A shielded, dense core

IRAM/PdBI H$^{13}$CO$^+$ and DCO$^+$

(Pety et al. 2007)

- 4 K DCO$^+$ lines less than 50'' from edge imply
  - Shielded: $A_v \geq 10$,
  - Cool: 10–20 K,
  - Dense: $n(H_2) \geq 2 \times 10^5$ cm$^{-3}$.

- Fractionation levels
  - $[\text{DCO}^+]/[\text{HCO}^+] = 2\%$ in dense core.
  - $[\text{DCO}^+]/[\text{HCO}^+] < 0.1\%$ in PDR gas.

- Note: Bright DCO$^+$ lines is a serendipitous discovery.
The Horsehead mane ID card: III.2 Behind a far UV illuminated PDR

**NTT/SOFI H$_2$ 2.1 $\mu$m + IRAM/PdBI HCO**

(Gerin et al. 2009)

- 1.5 K HCO lines at 15'' from edge imply
  - Illuminated: $A_v \sim 1.5$,
  - Warm: $T_{\text{gas}} \sim 100 - 200$ K,
  - Relatively dense: $n_H \sim 4 \times 10^4$ cm$^{-3}$.
- HCO Abundances in PDR gas
  - $[\text{HCO}]/[\text{H}_2] \sim 1.7 \times 10^{-9}$,
  - $[\text{HCO}]/[\text{H}^{13}\text{CO}^+] \sim 55$,
  - $[\text{HCO}]/[\text{HCO}^+] \sim 1$.
- HCO: A surface tracer of dense FUV illuminated molecular gas.
- Note: Bright HCO lines is a serendipitous discovery.
The Horsehead PDR ID card: III. Density profile

NTT/SOFI $H_2$ 2.1 $\mu$m + IRAM/PdBI $^{12}$CO and $C^{18}O$

(Habart et al. 2005)

- $H_2$ filament width ($\sim 5''$)
  $\Rightarrow$ PDR inclination on the plane-of-the-sky $< 5^\circ$.
- Tracer stratification
  $\Rightarrow$ Steep density gradient: $10^5$ cm$^{-3}$ in 10'' or 0.02 pc.
- Density + Thermal profiles
  $\Rightarrow$ Roughly uniform thermal pressure: $\sim 4 \times 10^6 K$ cm$^{-3}$.

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The Horsehead PDR ID card: IV. The kinetic temperature

VLA+Effelsberg NH\textsubscript{3} 1.3 cm rotation-inversion lines

(Pety et al., in prep.)

- \( T_{\text{rot}}(2, 2 - 1, 1) = \frac{41.18}{\ln \left( \frac{3.53 \int T(1, 1) d\nu}{\int T(2, 2) d\nu} \right)} \).
- From Effelsberg data only (\( \theta \sim 40'' \)): 15 K < \( T_{\text{rot}} \) < 25 K \( \Rightarrow \) 15 K < \( T_{\text{kin}} \) < 40 K.
- From Effelsberg+VLA data (\( \theta \sim 3'' \)): 15 K < \( T_{\text{rot}} \) < 35 K \( \Rightarrow \) 15 K < \( T_{\text{kin}} \) < 70 K.
PAHs in the Horsehead mane: I. Survival in HII region
Spitzer/IRS 6.2, 7.7, 8.6 and 11.3 µm AIBs + H₂ and NeII
(Compiègne et al. 2007)

- Observational facts:
  - Strong 11.3 µm emission in the HII region, correlated with NeII and Hα emission.
  - No associated 6.2, 7.7 or 8.6 µm emission in the HII region.

- Consequences:
  - PAHs may survive 5000 yrs in a HII region with $G_0 = 100$ and no photons above 25 eV.
  - 25-45% of neutral PAHs in HII region.
PAHs in the Horsehead mane: II.1 Link with the small hydrocarbons
IRAM/PdBI CCH, c-C$_3$H$_2$ and C$_4$H (Pety et al. 2005)

- Good spatial correlations of small hydrocarbons between them and with ISO 7 $\mu$m.
- Best PDR model fails to reproduce the abundances of the small hydrocarbons.
- Possible explanations:
  - Photo-erosion of PAHs (large C reservoirs).
  - Turbulent mixing of material produced in the shielded part (Lesaffre et al. 2007).
PAHs in the Horsehead mane: II.2 Link with the small hydrocarbons

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● Importance of multiple species observations:
  - Before $\text{DCO}^+$ observation: CCH hole is a deconvolution artifact.
  - After $\text{DCO}^+$ observation: CCH hole is an evidence of its depletion on grains in the cold core.
Sulfur chemistry: I. Importance of mapping
IRAM/PdBI CS (J=2–1) + IRAM/30m CS, C$^{34}$S and HCS$^+$
(Goicoechea et al. 2006)

- Different spatial morphologies of CS and small hydrocarbon emissions.
- Cross cuts only give rise to very different behavior depending on $\delta y \Rightarrow$ Mapping is essential (whenever possible).
**Sulfur chemistry: II. Importance of detailed modelling**

IRAM/PdBI CS (J=2–1) + IRAM/30m CS, C$_{34}^4$S and HCS$^+$

(Goicoechea et al. 2006)

- **Important improvement:** Line modelling through a Monte-Carlo radiative transfer.
- **Comment:** Large effort ⇒ Back to selected cross cuts for modelling purpose.
- **Physical result:** PDR model predicts a too step temperature decrease (Prediction: 10 K, observed: at least 30 K at $\delta x = 30''$).
**Sulfur chemistry: III. Importance of isotologues**

IRAM/PdBI CS (J=2–1) + IRAM/30m CS, C\(^{34}\)S and HCS\(^+\)

(Goicoechea et al. 2006)

- **Physical result:** Presence of a \(5.10^3\) cm\(^{-3}\) halo.

- **Comments:**
  - A difficult choice: Bright optically thick (with complex radiative effects for high dipole moment molecules) vs faint optically thin lines.
  - A must: Multi-line studies and isotopologue observations needed to understand excitation effects.
Sulfur chemistry: IV. Importance of reactive ions

IRAM/PdBI CS (J=2–1) + IRAM/30m CS, C$^{34}$S and HCS$^+$

(Goicoechea et al. 2006)

- Chemical result: $[S/H]_{PDR} = 0.25 [S/H]_{solar}$, i.e. almost undepleted sulfur abundance compared to diffuse ISM.
- Reason: Latest reaction rates and branching ratios (Montaigne et al. 2005)
  - HCS$^+$ + e$^-$ $\rightarrow$ CS + H (0.19 instead of 1)
  - HCS$^+$ + e$^-$ $\rightarrow$ CH + S and/or SH + C (0.81 instead of 0)
  - OCS$^+$ + e$^-$ $\rightarrow$ CO + S (0.83)
  - OCS$^+$ + e$^-$ $\rightarrow$ CS + O (0.14)
  - OCS$^+$ + e$^-$ $\rightarrow$ SO + C (0.03)
- Comment: Such faint lines would be difficult to observe with an interferometer $\Rightarrow$ Complementarity of interferometer and single-dish observation.
Sulfur chemistry: V. Follow-up
IRAM/30m CS, $\text{H}_2\text{S}$ and SO
(Goicoechea et al. in prep)

Follow-up:
Biased survey + mapping of some sulfur molecules
Chemistry of the formyl radical: I. Observations
IRAM/PdBI + IRAM/30m $^{13}\text{CO}^+$ and HCO (Gerin et al., 2009)

- Relative abundances
  - $[\text{HCO}]/[^{13}\text{CO}^+] < 1.6$ in dense core.
  - $[\text{HCO}]/[^{13}\text{CO}^+] \sim 55$ in PDR gas.
- A surface tracer.
Do we understand (i.e. do we reproduce) the “observed” abundances?

It is often easier to reproduce relative abundances (e.g. \([\text{HCO}] / [\text{H}^{13}\text{CO}^+]\)) than absolute ones (i.e. \([\text{HCO}] / [\text{H}]\)).
Ionization fraction profile: I. Models
(Goicoechea et al. 2009)

- Model ingredients
  - **Standard** cosmic ray ionization rate: $\zeta = 3 \times 10^{-17} \text{ s}^{-1}$
  - Metalicities:
    * **Standard** (strong depletion): $[M] = 10^{-9}$ (solid);
  - No PAHs.

- Ionization fraction (i.e. electronic abundance) set by
  \[
  n(e^-) = \sum_i n_i(\text{cations}^+) - \sum_i n_i(\text{anions}^-). \tag{1}
  \]

- 3 regions
  \[
  \begin{array}{lll}
  A_v & \text{Region kind} & \text{e}^- \text{ source} \\
  \lessgtr 2 & \text{UV irradiated} & \text{Ionization of C;} \\
  2 \text{ to } 6 & \text{Transition} & \text{Ionization of S;} \\
  \gtrsim 6 & \text{UV shielded} & \text{Ionization of metals, e.g. Fe, Mg, Na, ...}
  \end{array}
  \]
Ionization fraction profile: II.1 Observational probes
(Goicoechea et al. 2009)

- $H_3^+$ formation: $\propto \zeta_{CR} n_H$.
- $^{13}HCO^+$
  - Formation: Protonation + Fractionation
    * $^{13}CO + H_3^+ \rightarrow H^{13}CO^+ + H_2$;
    * $^{13}CO + H^{12}CO^+ \leftrightarrow H^{13}CO^+ + ^{12}CO + \Delta E(= 9 K)$.
  - Destruction: Dissociative recombination
    * $H^{13}CO^+ + e^- \rightarrow ^{13}CO + H$.
- $^2HCO^+$
  - Formation: Deuteration
    * $H_3^+ + HD \leftrightarrow H_2D^+ + H_2 + \Delta E(= 232 K)$;
    * $CO + H_2D^+ \rightarrow DCO^+ + H_2$.
  - Destruction: Dissociative recombination
    * $DCO^+ + e^- \rightarrow CO + D$.
- $HOC^+$
  - Formation:
    * $C^+ + H_2O \rightarrow HCO^+/HOC^+ + H$;
    * $CO^+ + H_2 \rightarrow HCO^+/HOC^+ + H$.
  - Destruction: Isomerization
    * $HOC^+ + H_2 \rightarrow HCO^+ + H_2$. 
Ionization fraction profile: II.2 Observational probes
(Goicoechea et al. 2009)

- Shielded core:
  - Absolute abundances correct in strong metal depletion case.
  - $[\text{DCO}^+] \propto [\text{H}^{13}\text{CO}^+]$ (common destruction mechanism).
  $\Rightarrow$ Low ionization fraction.

- Illuminated PDR:
  - $[\text{HOC}^+] /[\text{H}^{13}\text{CO}^+]$ correct;
  - Measured absolute abundances larger than predicted.
  $\Rightarrow$ High ionization fraction.
Ionization fraction profile: III.1 Influence of PAHs
(Goicoechea et al. 2009)

- Introduction of PAHs:
  - $[\text{PAH}] = 10^{-7}$ or 1% of the dust mass;
  - Typical size: 100 carbon atoms;
  - No evolution of the distribution with $A_v$.

- Illuminated region: No influence because $C^+$ abundance is larger by order of magnitude.

- Transition region:

- Shielded region:
Ionization fraction profile: **III.2 Influence of PAHs**  
(Goicoechea et al. 2009)

- Introduction of PAHs:  
  \([\text{PAH}] = 10^{-7}, \sim 100\ \text{carbons}\).
- Illuminated region: No influence.
- Transition region:
  - Without PAHs:
    * Sulfur ionization = Source of electrons.
  - With PAHs:
    * PAH\(^-\) formation: Electron attachment.  
      - \(\text{PAH} + e^- \rightarrow \text{PAH}^- + h\nu\).
    * PAH\(^-\) destruction:
      - \(\text{PAH}^- + h\nu \rightarrow \text{PAH} + e^-\);  
      - Neutralization by cations.
  - High electron density and low UV field \(\Rightarrow\) enough PAH\(^-\) to neutralize \(S^+\) \(\Rightarrow\) Much more neutral sulfur for the same elemental abundance.
- Shielded region:

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Ionization fraction profile: III.3 Influence of PAHs
(Goicoechea et al. 2009)

- Introduction of PAHs: 
  \([\text{PAH}] = 10^{-7}, \sim 100\) carbons.

- Illuminated region: No influence.

- Transition region: Much more neutral sulfur for the same elemental abundance.

- Shielded region:
  - Without PAHs:
    * Fast charge transfer to metal \(m^+ + M \rightarrow m + M^+\);
    * Slow metal neutralization by electrons.
  
  \[\Rightarrow \text{Metals} = \text{electron source}.\]

  - With PAHs:
    * PAH\(^-\) easily formed through electron attachment \(\text{PAH} + e^- \rightarrow \text{PAH}^- + h\nu\);
    * Quick metal neutralization by PAH\(^-\).

  \[\Rightarrow \text{PAH}^- \text{ more abundant than electrons and neutral metals}.\]
Ionization fraction profile: **III.4 Influence of PAHs**

(Goicoechea et al. 2009)

- **Introduction of PAHs:** $[\text{PAH}] = 10^{-7}, \sim 100 \text{ carbons}$.  

- **Illuminated region:** No influence.

- **Transition region:** Much more neutral sulfur for the same elemental abundance.

- **Shielded region:** PAH$^-$ more abundant than electrons and neutral metals.

- **Degeneracy:**  
  - Standard metalicity, no PAHs;  
  - High metalicity and standard PAHs.

- **Question:** Do PAHs exist in the shielded region?

Test metallicity for $\zeta_{CR}=3 \times 10^{-17} \text{ s}^{-1}$
The PDRs and Herschel: I. HIFI

- The Herschel satellite:
  - 3.5 m single-dish antenna.
  - Wavelengths/frequencies: from 450 GHz (672 µm) to 5.5 THz (55 µm).
  - Angular resolution: from 40'' to 10''.
  - Cooled instruments ⇒ 3 years life.
- HIFI: 480 - 1910 GHz (625 - 157 µm)
  - Single-beam heterodyne instrument ⇒ high spectral resolution.
  - Key science targets for PDR studies:
    * CII 158 µm, NII 206 µm fine structure lines: PDR cooling lines, kinematics of the PDR/ionized gas interface.
    * Water (H₂O, HDO, H₂¹⁸O): Thermal emission is visible only from space.
    * Hydrides (NH, NH₂, OH⁺, CH⁺, H₃O⁺,…): Light molecules ⇒ high frequency rotational lines: Building blocks of photo-induced / warm chemistry.
The PDRs and Herschel: I. PACS

- PACS:
  - Instrument:
    * Multi-pixel: $5 \times 5 \Rightarrow 50''$ field-of-view.
    * Medium spectral resolution: $R \sim 2000 - 4000 \Rightarrow$ unresolved line profiles.
    * Sensitive.
  - Key science targets for PDR studies:
    * Far-IR dust: Peak of dust thermal emission (i.e. dust heated by UV photons release their energy in the Far-IR). In combination with [CII] and [OI], the dust Far-IR spectro-energy distribution gives access to the photo-electric heating mechanism.
    * OI 63 and 145 $\mu$m, CII 158 $\mu$m: Physical conditions in PDRs ($G_0$, $n$, $T$).
    * OIII 88 $\mu$m, NIII 57 $\mu$m, NII 122 and 206 $\mu$m: Physical properties of ionized (HII) gas ($n_e$, $T_e$, ...).
    * High-J lines of molecules ($H_2O$, OH, CO, NH$_3$, ...).
On the need of consistency to make reliable observational benchmarks for models

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The Horsehead mane: An observational benchmark for PDR models

- Well understood, simple geometry: almost 1D, edge-on.
- Well constrained density.
- Current effort to constrain the thermal profile.
- Rich chemistry (i.e. lot's of surprises).
- Close-by (400 pc), low illumination ($\chi \sim 60$), high density ($10^5 \text{ cm}^{-3}$)
  $\Rightarrow$ typical spatial scales: 1 to 50″.

$\Rightarrow$ Good source to serve as reference to models.
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An observational benchmark for PDR models

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Bibliography

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