Molecular cloud surfaces: PDRs everywhere

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Overview

- What are molecular clouds?
  - The simple picture
    - Success
    - Failures
  - The fractal picture
    - Success
    - Failures
  - The dynamic picture
    - Success
    - Failures
- Ways forward

Disclaimer: $A_V \lesssim 5$, i.e. cloud surfaces only, here
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The simple picture

- dense “blobs” of interstellar matter
- visible in CO
- in pressure- and virial equilibrium
- condensations form stars

Hogerheijde et al. (1998)
Chemical structure

Density profile and external UV field produce chemical gradients:

KOSMA-τ model of a cloud with $\chi = 1, M_{\text{tot}} = 100M_\odot, n = 500 \text{ cm}^{-3}$

- There is no “molecular cloud”. Each molecule sees a different size of the cloud.
- None of the mm/sub-mm tracers measures $\text{H}_2$. $\text{H}_2$ is molecular where many other molecules are dissociated.
- The region of strong chemical gradients is traced by [CⅠ].
**H$_2$ fraction**

Arabadjis & Bregman (1999): X-ray data  
Savage et al. (1977): UV data

- up to 50% of the CNM+WNM in solar neighbourhood is molecular (Savage 1977)
- $f_{H_2}$ is a steep function of $N(H_{tot})$, with a critical column density at about $5 \times 10^{20}$ cm$^{-2}$ (Savage et al. 1977, Liszt & Lucas 2001)
CO fraction

- CO is efficiently formed at $N(H_{\text{tot}}) \gtrsim 2 \times 10^{21} \text{ cm}^{-2}$ ($A_V \gtrsim 1$)
- $N(\text{CO}) \propto N(H_2)^2$ (Liszt & Lucas 2001)

Heyer et al. (1998): FCRAO survey of the Outer Galaxy

22% of the lines of sight through the Outer Galaxy show CO emission above a sensitivity limit of $\approx 2.4 \text{ K}$ for the CO 1–0 line.
[Cl] observations

[Cl] should trace the transitional region where H₂ is molecular, and other molecules only start to form.

FCRAO and KOSMA observations of IC348 in CO 1-0 (left contours), $^{13}$CO 1-0 (central contours) and [Cl] (colors), right panel: [Cl]/$^{13}$CO 1-0 line ratio, Sun et al. (2007)

- [Cl] enhanced at the surface, but also strong in the cloud
[Cl] observations

Observations at the somewhat larger scale:

- [Cl] is much more extended than CO, but also strong at the bulk of the material
- [Cl] is often a molecular cloud volume tracer instead of a surface tracer

Orion A observations in CO and [Cl], Plume et al. (2000)
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[C I] observations

Explanation:

The clouds consist to a large part of surfaces

Clouds are not smooth, but complex, filamentary, fractal.

- fractal structures are created by a cascade of interstellar turbulence
The fractal picture

The $\Delta$-variance spectrum measures the amount of structure on different size scales. A power-law indicates self-similar behaviour, i.e. an invariant scaling independent from the considered size.

- the turbulent structuring creates surfaces everywhere and at each scales
- UV radiation can deeply penetrate the clouds

$\Delta$-variance spectra of the Orion maps (Plume et al. 2000)
The fractal picture

The $\Delta$-variance analysis shows a typical power-spectral index around $\beta \approx 2.7$ (Ossenkopf et al. 2002).

This can be represented by an ensemble of clumps with adapted mass-spectrum and mass-size relation (Stutzki et al. 1998, Heithausen et al. 1998):

\[
\frac{dN}{dM} \propto M^{-\alpha} \quad \alpha = 1.8 \\
M \propto R^\gamma \quad \gamma = 2.3
\]

Zielinsky et al. (2000)
The fractal picture

Explains Galactic FIR line emission as observed by COBE (Fixsen et al. 1999):

Failures

CO at low column densities

Wide spread filamentary $^{12}\text{CO}$ emission at a low column densities, $\int T \, dv \lesssim 2 \text{ K km/s}$:

Schuster, Lefloch, Ungerechts, Thum, Gueth, Sterzik, Wiesemeyer, Hily-Blant (2004): 4.1-4.4 km/s
CO at low column densities

Detailed quantitative analysis by Hily-Blant & Falgarone (2006):

- filaments:
  - pure velocity structures
  - $D \approx 0.03$ pc, $\Delta v \approx 0.35$ km/s
  - $N(H_{\text{tot}}) < 3 \times 10^{20}$ cm$^{-3}$ $\Rightarrow A_V < 0.15$, $N_{\text{CO}} \approx 10^{15}$ cm$^{-3}$

- overall line wing region:
  - total column correponds to $A_V \lesssim 0.8$
  - gas is warmer and more diluted than average
Molecules at low column densities

Classical example – ζ Oph

\(A_V \approx 0.8, \chi \approx 3.5\):

\[
\begin{array}{|c|c|c|}
\hline
 & \text{^{12}CO} & \text{^{13}CO} \\
\hline
\text{model} & \lesssim 2 \times 10^{14} \text{ cm}^{-2} & \lesssim 3 \times 10^{12} \text{ cm}^{-2} \\
\text{observations} & 2 \times 10^{15} \text{ cm}^{-2} & 4 \times 10^{13} \text{ cm}^{-2} \\
\hline
\end{array}
\]

(van Dishoeck & Black 1988)

Large quantities of CH\(^+\), HCO\(^+\), OH, CO, C\(_2\)H, NH\(_3\), H\(_2\)CO, CN, CS, HCN, HNC, SO, C\(_3\)H\(_2\), H\(_2\)O at low column densities. (Lucas and Liszt 2002, Liszt et al. 2006, Neufeld et al. 2003)

Similarities between dark cloud and diffuse cloud abundance patterns.

Absorption spectra towards B0355+508 (Liszt et al. 2006)
Static clouds with a turbulent structure?

- Turbulent motions stabilize against collapse, but also destroy the clouds.
- Molecular cloud lifetime < crossing time (Falgarone et al. 2004)

Example:

\[ n_H = 300 \, \text{cm}^{-3}, A_V = 5 \implies D = 10 \, \text{pc}; \quad \text{with } v_{\text{turb}} = 10 \, \text{km/s} \implies \tau_{\text{cross}} = 1 \, \text{Myr} \]

Turbulent motions are rapidly damped (Mac Low & Klessen 2004):  

Damping of turbulence leads to bending of structure cascade (Ossenkopf & Mac Low 2002). This is not observed large scale driving most be either permanent or recent.

Molecular clouds are continuously restructured by ubiquitous turbulence.
The dynamic picture

- Turbulence in molecular clouds is large-scale driven (Ossenkopf & Mac Low 2002).
- Turbulent clouds are just high-density knots in large scale flows of atomic material (Brunt 2003)
- Clouds are essentially shock-dominated structures (Hartmann et al. 2001)

Implications:

- clouds are short lived (1 ... 2 Myr)
- turbulent mass transport
- turbulent diffusion
- heating due to turbulence dissipation

Hartmann et al. (2001): triggering of molecular cloud and star formation by large scale flows, rapid dispersal of gas by newly formed stars

Problem:
At standard H$_2$ formation rate, $\approx 10^9 \text{yr}/n_H[\text{cm}^{-3}]$, $\tau_{H_2}(300 \text{ cm}^{-3}) = 3 \text{ Myr} > \tau_{\text{cross}}$
**Fast H\(_2\) formation**

**Solution:** H\(_2\) formation in short times at high densities created in shocks

Bergin et al. (2004):
- H\(_2\) formation in a 1-D slow-velocity (10 km/s) shock in the atomic gas (1 cm\(^{-3}\)).
- H\(_2\) is efficiently formed and self-shielded.
- CO forms for \(A_V > 0.7\) on timescales of 10-20 Myr
Fast $H_2$ formation

Distribution of the formed $H_2$ by turbulent advection:

Glover & Mac Low (2007):

Turbulent cloud simulation including $H_2$ formation/self-shielding

- wide density distribution
- fast $H_2$ formation at $n_H \gtrsim 300 \, \text{cm}^{-3}$
- turbulent redistribution of $H_2$ gas
- $H_2$ formation rate accelerates by a factor 3-5
- conversion of $\approx 40\%$ of the hydrogen into $H_2$ in the scale of 1-2 Myr
Hot H$_2$

Hot H$_2$ in PDRs and diffuse clouds:

Morris et al. (2004): NGC 7129: Excitation of H$_2$ rotational lines too high to be explained by UV pumping;
Falgarone et al. (2005): same conclusion for diffuse clouds

Solution:

- Chemistry driven by turbulent dissipation: \( \Rightarrow \) talk by Edith Falgarone
- Chemistry driven by turbulent shocks: \( \Rightarrow \) talk by Cesare Cecchi-Pestillini
- Chemistry driven by turbulent mixing at interfaces: \( \Rightarrow \) talk by Maryvonne Gerin

\( \Rightarrow \) warm H$_2$ + enhanced formation of HCO$^+$, CH$^+$, CH, H$_3^+$, OH, H$_2$O
Problems

- Time-scales still too short for many chemical species

- $f_{\text{CH}}$ is known to drop in dark clouds (see PDR models), but CH/CO is factor 3 larger in dark clouds

- For more problems see next talk

Liszt & Lucas (2002)
Ways forward

Observations

Herschel/HIFI:

- Continuous frequency coverage 480–1250 GHz and 1410-1910 GHz
- Spectral resolution 130 kHz–1.1 MHz
- Instantaneous bandwidth 4 GHz (2.4 GHz above 1410 GHz)
- Near-quantum noise limit sensitivity ($\approx 3h\nu/k$)
- Two polarizations simultaneously
Observations

HIFI and PACS:

- provide a unique way to study the chemical inventory in dense interstellar clouds:
- observe ground-state transitions of key species: CH, NH, H₂O, OH (PACS), CH⁺, NH⁺, OH⁺, H₃O⁺

With the spectral resolution of HIFI we can

- resolve shock structures in turbulent velocity field
- study the dynamical structure of molecular clouds
- resolve the three-dimensional abundance distribution of species

Hennebelle & Perault (2000)

Deadline for open-time key project proposals: October 25, 2007
Conclusions

• a large fraction of the ISM gas is molecular
• most of that is only partially molecular
• $\text{H}_2$ seen at many different conditions, but a large fraction invisible in CO

• There is no simple answer to what a molecular cloud is.
  - different molecules are found in different regions
  - even for $\text{H}_2$, different thresholds for “molecular gas” need to be defined depending on the physical/chemical processes considered

• Clouds are turbulent. This implies
  - fractal structures everywhere
  - short lived clouds, non-equilibrium chemistry
  - turbulent mixing, turbulent transport, turbulent dissipation

• Mapping observations of various tracers resolving the turbulent structure in space and velocity are needed.