Interstellar Medium in galaxies

1. The atomic and molecular components
2. Small scale structure, the Milky Way
3. ISM in external galaxies, SFR, ULIRGs
4. Accretion and evolution in a cosmological context

Françoise Combes, Paris Observatory
**HI line 21cm**

**Ewen & Purcell 1951**: Discovery of HI 21cm line from the Galaxy

**Spin-flip transition**, in the ground state $1^2S_{1/2}$

Predicted by van de Hulst in 1945

$F=1 \rightarrow F=0$, distant from $h\nu = kT$, with $T=0.07 \text{ K} \ll 3 \text{ K}$

$v = 1420 \text{ MHz}$

$A = 2.9 \times 10^{-15} \text{ s}^{-1}$
Extension of galaxies in HI

Dark halo exploration

NGC 5055  Sbc

Milky Way-like spiral ($10^9 M_\odot$ of HI): M83

M83: optical
NGC 5055, rotation curve (Battaglia et al 2006)
Channel maps
Spider diagram
N5055
Rotation curve of NGC 5055 (Battaglia et al 2006)

Bump in the center, and decrease by 25km/s

⇒ Disk maximum M/L > 1.4
Warping of the plane, lopsidedness

N5055: warp fit
By tilted ring model
R(HI) = 40kpc
The warp is better fit when the center is shifted in the outer parts.

Symmetrical ➞ long-lived?
1.5 Gy period
Towards the companion UGC 8313

➤ As if the galaxy was in two regimes:

-- Dominated by the visible matter inside 10kpc
-- Then domination of the dark halo, with varying center and Vsys
HI rotation curves: conspiracy?
$\sigma_{DM}/\sigma_{HI} = \text{cste}$

In average $\sim 10$

Hoekstra et al (2001)
Splash of interstellar gas

HI

Messier 81, Messier 82, NGC 3077
High Velocity Clouds infalling onto the Galaxy

Origin still unknown
Their mass depends on their distance \((D^2)\)
Residuals from the formation of Local Group? \(\Rightarrow\) very massive
Or just infalling from Magellanic Clouds?

Multiple origins
Also, fountain effect after formation of supernovae..

Wakker et al. 99
The Magellanic Stream

Detected in neutral hydrogen \( \text{HI} \) at 21cm in wavelength
As much HI gas in Small as in Large Magellanic Clouds

The gas must have been dragged out of the SMC, according to simulations

Putman et al 98
Reconstitution of the interaction

Low mass ratio, of the order of a few \( \% \)

Several passages since the formation of Local Group

Clouds are passing in front

Constraints on the Milky Way mass

\( V \sim 200 \text{ km/s} \)
HI map of Large Magellanic Cloud LMC


Large range of 2.8 in scales, from 15pc

Determination of the cloud mass spectrum

Bubbles due to SF
Size distribution
Feedback due to star formation

Holes and shells

Same power-law distribution as that of clumps

Fractal with $D=1.4$

Extension in UV (GALEX)

NGC 4625 interacting with NGC 4618 (Gil de Paz et al 2005)
Halpha contours, superposed to the B-image, compared to the UV image (Gil de Paz et al 2005)

UV extends to 4 times the optical radius and coincides with HI peaks

Small companion NGC 4625A, close to the main galaxy
XUV disks, M83 and others

Bluer regions outside
Younger SF + scattered light

M83, Galex, +HI contours (red)
Thilker et al 2005
Yellow line RH_{HII}, 10M_\odot/pc^2 in HI
Star formation rate: Schmidt law

SFR empirically proportional to gas density, exponent n=1.5 (global Schmidt law, not local, *Kennicutt 1998*)
Same for interacting and non-interacting

\[ \Sigma_{\text{SFR}} \sim \Sigma g^{1.5} \]

**Processes:** Jeans instability, dynamical time \( \rho^{3/2} \)
or Cloud-cloud collisions (*Elmegreen 1998*)

+ density threshold
The $\text{H}_2$ molecule

- Symmetrical, no dipole
- Quadrupolar transitions $\Delta J = \pm 2$
- Light molecule $\Rightarrow$ low inertial moment and high energy levels
- **Para** (even $J$) and **ortho** (odd $J$) molecules (behave as two different species)
H$_2$ is the most stable form of hydrogen at low T dominant in planetary atmospheres?

**Formation:** on dust grains at 10K
However formation still possible in primordial gas (H + H$^-$ Palla et al 1983)

**Destruction:** through UV photons (Ly band)
Shielded by HI, since the photodissociation continuum starts at 14.7 eV, and photo-ionization at 15.6 eV (HI ionization at 13.6 eV)

**Self-shielding** from low column densities
$10^{20}$ cm$^{-2}$ in standard UV field

H$_2$ will be present, while other molecules such as CO would be already photo-dissociated
Potential curves involved in the Lyman and Werner bands (Roueff 2000)
Ortho-Para transitions?

• Formation in the para state not obvious
• Large energy of formation $2.25 \text{ eV/atom}$
• ortho-para conversion in collisions $\text{H}^+ + \text{H}_2$

• $n(\text{O})/n(\text{P}) \sim \exp(-170/T)$
• Anormal ratios observed (ISO)

• IR lines $J=2-1$ at $42 \mu$, $1-0$ at $84 \mu$?
• $A = 10^{-10} \text{ cm}^3/\text{s}$ (Black & Dalgarno 1976)
• $A = 2 \times 10^{-10} \text{ cm}^3/\text{s}$ (Gerlich 1990) reaction favors o-$\text{H}_2$
Infrared Lines of H$_2$

- Ground state, with ISO (28, 17, 12, 9μ)
- S(0), S(1), S(2), S(3)

- From the ground, 2.2 μ, v=1-0  S(1)
- excitation by shocks, SN, outflows
- or UV-pumping in starbursts, X-ray, AGN
- require T > 2000K, nH$_2$ > 10$^4$cm$^{-3}$
- exceptional merger N6240: 0.01% of L in the 2.2 μ line (all vibration lines 0.1%?)
H₂ distribution in NGC891 (Valentijn, van der Werf 1999)
S(0) filled; S(1) open – CO profile (full line)
Large quantities of H$_2$ revealed by ISO

NGC 891, Pure rotational H$_2$ lines S(0) & S(1)
S(0) wider: more extended?
Derived N(H$_2$)/N(HI) = 20; Dark Matter?
$\text{H}_2 \ \nu=1-0 \ S(1) \ 2.15\mu \ \text{in NGC 6240}$

van der Werf et al (2000) HST
UV Lines of $\text{H}_2$

- Absorption lines with FUSE ($\text{Av} < 1.5$)
- Very sensitive technique, down to column densities of $\text{NH}_2 \ 10^{14} \text{ cm}^{-2}$

- Ubiquitous $\text{H}_2$ in our Galaxy (Shull et al 2000, Rachford et al 2001) translucent or diffuse clouds

- Absorption in LMC/SMC reduced $\text{H}_2$ abundances, high UV field (Tumlinson et al 2002)

- High Velocity Clouds detected (Richter et al 2001) in $\text{H}_2$
  - (not in CO)
FUSE Spectrum of the LMC star Sk-67-166 (Tumlinson et al 2002)

$NH_2 = 5.5 \times 10^{15} cm^{-2}$
Detection of $\text{H}_2$ in absorption by FUSE in HVCs
Murphy et al (2000), Sembach et al 2001
The CO Tracer

- In galaxies, $\text{H}_2$ is traced by CO rotational lines
- $\text{CO}/\text{H}_2 \sim 10^{-5}$
- CO are excited by collision with $\text{H}_2$
- The dipole moment of CO is relatively weak
  - $\mu \sim 0.1$ Debye

- Spontaneous de-excitation rate $A_{ul} \propto \mu^2$
- $A_{ul}$ is low, molecules remain excited in low-density region about 300 cm$^{-3}$
• Competition between collisional excitation and radiative transitions, to be excited above the 2.7K background

• J=1 level of CO is at 5.2K

• The competition is quantified by the ratio $C_{ul}/A_{ul}$

• varies as $n(H_2)T^{1/2}/(\nu^3 \mu^2)$

• Critical density $n_{crit}$ for which $C_{ul}/A_{ul} = 1$

<table>
<thead>
<tr>
<th>Molecule</th>
<th>CO</th>
<th>NH₃</th>
<th>CS</th>
<th>HCN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ (Debye)</td>
<td>0.1</td>
<td>1.5</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>$n_{crit}$ (cm⁻³)</td>
<td>4E4</td>
<td>1.1E5</td>
<td>1.1E6</td>
<td>1.6E7</td>
</tr>
</tbody>
</table>
Various tracers can be used, CO for the wide scale more diffuse and extended medium, the dense cores by HCN, CS, etc..

The CO lines (J=1-0 at 2.6mm, J=2-1 at 1.3mm) are most often optically thick
At least locally every molecular cloud is optically thick
Although the "macroscopic" depth is not realised in general, due to velocity gradients

Relation between CO integrated emission and H$_2$ column density?
Is it proportional? How to calibrate?
NGC 6946 mid-infrared image (Helou et al. 1996)
ISO-CAM map: 7$m_{m}$-green, 15$m_{m}$-red
12.5’ x 12.5’ field; 3” x 3” pixels; 7” beam width

Gemini, Michaud 2005
NGC 6946  CO(2-1) map 13'' beam
IRAM 30m
Spectra, Weliachew et al 1988
• Isotopic molecule $^{13}$CO, UV lines
• Statistics of "standard" clouds
• The Virial relation

1- Use the isotope $^{13}$CO much less abundant at the solar radius: Ratio $\sim 60$
therefore $^{13}$CO lines more optically thin
A standard cloud in the MW has $\tau_{\text{CO}} \sim 10$
and $\tau_{13} \sim 0.1$
The average ratio between integrated CO and $^{13}$CO intensities is of the order of 10
Milky Way

\( V^2 r \sim GM \)

Virial mass versus \( L_{\text{CO}} \)

\( M_{\text{vt}} = 39L_{\text{CO}}^{0.81} \)

Slope is not 1

Solomon et al 1987
Messier 51, CO rich

Optical HST

CO OVRO

Spitzer IR

Radio, Magnetic field
Messier 81, CO poor

M81, HI line VLA

Spitzer, 4, 8, 24 microns
$L_{\text{CO}}/M(\text{HI}) \propto (\text{O/H})^{2.2}$

Confirmed by Taylor & Kobulnicky (98)
M82, Spitzer, dust FIR (PAH)

M82 in CO Streamers
Red: optical
Blue: Hα
Green CO (OVRO)
Another tracer: cold dust

At 1mm, the emission is Rayleigh-Jeans

\[ B(\nu, T) \sim 2k \frac{T}{\lambda^2} \]

flux quasi-linear in T (between 20 and 40K)

In general optically thin emission

Proportional to metallicity Z

Z decreases exponentially with radius
When the molecular component dominates in galaxies, the CO emission profile follows the dust profile (example NGC 891).

When the HI dominates, on the contrary, the dust does not fall as rapidly as CO with radius, but follows more the HI (example NGC 4565).

CO might be a poor tracer of $\text{H}_2$. 
Radial profiles N891 (Guélin et al 93) & N4565 (Neininger et al 96)
The excitation effects combine to metallicity. Explains why it drops more rapidly than dust with radius.

CO(2-1) line tells us about excitation. Boarder of galaxies, CO subthermally excited.

When optically thick CO21/CO10 ratio ~1. If optically thin, and same $T_{ex}$, could reach 4. But in general < 1 in the disk of galaxies.

$T_{ex}$ (21) < $T_{ex}$ (10) upper level not populated even if $T_{kin}$ would have allowed them.
Summary on the H$_2$ component

The H$_2$ molecule is **invisible**, in cold molecular clouds (the bulk of the mass!)

CO is **not a good tracer**, both because metallicity effect (non-linear, since depending on UV flux, self-shielding), and excitation

Very important to have other tracers
dense core tracers, HCN, HCO+, isotopes..

H$_2$ pure **rotational** lines, also a tracer of the "warm" H$_2$, always present when cold H$_2$ is there
CO in the Milky Way

Dame et al. 2001
Comparison with an optical image, of the CO clouds within 2.5kpc distance (within 10 to 35km/s)
Dame et al (2001)
CO Distribution and Spiral structure of the Milky Way

How to obtain distances?

- Kinematic models
  Determination of the rotation curve, from terminal velocities

Assumption of circular velocity for the gas

Ambiguities of distance, for material at longitudes below 90deg

To remove the degeneracy: the latitude or height above the plane
Can play a role statistically

Also the distance of the near stars, determined by their spectrum or by absorption (in front or behind)
Locus of tangent points

Ambiguity of distances

\[ V_{\text{rad}} (r,l) = R_{\text{sun}} \sin l (\Omega(R)-\Omega_{\text{sun}}) \]
Milky Way

Nakanishi & Sofue (2003) HI disk reconstituted
CO Radial Distribution

- Large concentration in the center
- Hole around 2 kpc
- Galactic Molecular ring between 4 and 8 kpc
- Exponential radial decrease in average
Spiral Structure

- Evidence of a spiral structure, through the l-V diagram
- Very difficult to deproject
- **Barred** structure (through the orbits, parallelogram..)
- Best is to build N-body models (cf Mulder & Liem 86, Fux 99)
- Second (**nuclear**) bar? (visible with 2MASS, Alard 2001)
The inner Galaxy

Always a big puzzle: forbidden velocities in the center

Expansion (Oort 77)? Explosion from the center? (Sanders 76)
Bar potential (Peters 1975)

Bar directly seen in COBE-DIRBE (Dwek et al 95)
Interpretation in terms of periodic orbits in a bar potential
parallel x1 orbits, perpendicular x2 orbits (Binney et al 97)

Characteristic parallelogram
Nuclear disk decoupled from the main disk
Expanding molecular ring

-0.6° < b < 0.6°

-0.1° < b < 0.1°

Clump 1

Clump 2

3kpc arm

parallelogram

$^{13}$CO Bally et al (1988)

$^{12}$CO Bally et al 87
From Fux (1999)
N-body simulations + SPH

Bar taken from DIRBE
The center of the bar wanders

Gas flow asymmetric non-stationary

Transient

3 kpc arm is a spiral round the bar

Parallelogram interpreted as leading dust-lanes
Bania's clump and V-elongated features near l=55° are gas lumps crossing the dust-lane shocks

Inclination of the bar 25°

Corotation radius 4.5 kpc

b/a = 0.6

Other features: inclined plane in the center

strong m=1
Fux (1999)

Velocities above the circular model

The region around 3kpc arm is subject to strong non-circular motions

Strong asymmetries
Interpretation of the central l-V diagram from Fux (1999)
x2 orbits are almost circular
x1 cusped orbits produce the parallelogram
Taurus Molecular Cloud at 100pc from the Sun

Fractal Structure

IRAS Emission at 100μ of heated dust

Self-similar structure (except for spatial resolution!)
CO mapping with FCRAO of 2nd quadrant (Mark Heyer et al)
Clouds mapped in HI 21cm absorption

3C138

10 AU

VLBA, or VLBI

(Davis et al 96, Faison et al 98)
Fractal Structure – Scaling Laws

Self-similarity -- relations from Larson (1981)

Relations between size and linewidth $\Delta V \sim R^q \quad 0.3 < q < 0.5$

Virialisation at all scales $\Delta V^2 \sim M/R$
(debate at small scale, where there is no good mass tracer)

Size-Mass $M(r) \sim r^D \quad 1.6 < D < 2$

Density decreases as $\sim R^{-\alpha} \quad 1 < \alpha < 1.4$
Formation by Jeans recursive fragmentation?

- a hierarchical fractal

\[ M_L = N M_{L-1} \]
\[ r_L^D = N r_{L-1}^D \]
\[ \alpha = r_{L-1}/r_L = N^{-1/D} \]

cf Pfenniger & Combes 1994

\[ D = 2.2 \]
\[ D = 2 \]
\[ D = 1.5 \]
\[ D = 1.8 \]
Projected mass log scale (15 mag)

N=10, L=9

The surface filling factor depends strongly on D

< 1% for D=1.7
Origin of the heating?

Star formation in the center of the optical disk

**Gravitational instabilities** in quiet areas
Toomre criterion for stability
self-regulating

**Flaring of the plane:**
thickness increasing linearly with radius

visible in HI, and also in the molecular plane
The total density in the plane is decreasing

Less restoring force, same velocity dispersion

**==> increased thickness**
Flaring of the HI plane almost linear

\[ h_g = h_0 + 0.045 \times R \]

Merrifield (1992)

The CO/H\textsubscript{2} follows the flare, and also the warp

Grabelsky et al (1987)
HI and H$_2$ Flaring
Warping of the plane

Spectacular in HI
Asymmetrical (only one side)

Corrugations (larger amplitude than $h_g$)

The CO follows the warp

Also observed in external galaxies, in particular M31

CO observed with 2 velocities, at each crossing of the warped plane
High Velocity Clouds

Accreting Low-Metallicity Gas

• Observed on 20% of the sky
Spitzer Extragalactic First-Look Survey

100 μm dust emission
HI Maps

Lockman and Condon 2005
GBT Observations
Spitzer and IRAS Images
Infrared-HI correlation

\[ I_\nu (x,y) = \Sigma_i \alpha_\nu^i N_{\text{HI}}^i (x,y) + C_\nu (x,y) \]

- Multivariate regression to estimate the infrared emissivity of each HI component.

→ First detection of dust emission in the HVC

- HVC Emissivity at \(100 \, \mu m\) ~ **10 times smaller** than local gas, but **only a factor 2 smaller** at \(160 \, \mu m\)

⇒ Colder dust

*Miville-Deschênes et al 2005*
Gamma-ray surveys

In the Milky Way, the detection of gamma-rays of high energy (> 100Mev) is a tracer of all matter

Nucleons (HI, H₂, HII..) interact with cosmic rays to produce pions, that disintegrate in gamma-rays

Early surveys showed that the CO/H₂ conversion ratio must not be constant throughout the Galaxy (Wolfendale et al 1977)
\( \gamma \)-rays: Dark gas in the solar neighborhood

Dust detected in B-V (by extinction) and in emission at 3mm

\( \gamma \)-Emission associated to the dark gas

\( \text{H}_2 \times \text{a factor 2 (or more)} \)

Grenier et al (2005)
Conclusion: ISM in MW

• About comparable amounts of H$_2$ and HI gas in the MW
• M(H$_2$) $\sim$ 2-3 $10^9$ Mo

Very different radial repartition

H$_2$ is centrally concentrated, then in a molecular ring 4-8kpc

HI depleted in the center
and much more radially extended

Repartition in clouds, GMC of $10^6$Mo -- H$_2$ clumpiness

Fractal structure of molecular clouds
same flare and warping