The Molecular Interstellar Medium at Low Metallicities

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The MW and the Magellanic Clouds from Chajnantor, ALMA site
Most galaxies are low mass and low metallicity
(also, outer galactic disks)

Robertson & Kravtsov (2008)
Gnedin, Tassis, & Kravtsov (2009)
Narayanan et al. (2008)
Krumholz et al. (2008, 2009)
Gnedin & Kravtsov (2010)

Baldry et al. (2008)
Outline

1. Background: The structure of molecular clouds at low metallicities
2. Overview of observations
3. Relation between molecular gas and star formation
4. Perspectives for future research
The Structure of the Molecular ISM

HST imaging of the clouds in the Carina Nebula

N. Smith
No CO but active star formation?

- Less C and O ⇒ slower CO formation
- Less dust ⇒ faster CO photodissociation

Homonuclear, no permanent dipole. Ground quadrupole transition E~500 K

Chemically favored in dark clouds. Ground dipole transition E~5.5 K
Structure of Photodissociation Regions

Dust controls UV extinction and physical sizes

HII  HI  Self & cross shielded  H$_2$

C$^+$ + e$^-$ → C
C$^+$ + S → C + S$^+$
C + γ → C$^+$

C + OH → CO + H
CO + γ → C + O

Dust controls UV extinction and physical sizes

 Increasing $A_v$

HII region  PDR  Dark cloud

T~10,000 K  T ~ 1,000 to 10 K  T ~ 10 K
Clouds have substructure: clumpiness

- Widespread [C II] and [C I] emission
- Direct evidence of clumping in all scales

(e.g., Stutzki et al. 1988; Marscher et al. 1994)
As metallicity and dust-to-gas ratios decrease, \( A_v \sim 1 \) moves deeper into clumps of constant column density.

CO disappears when \( A_v < 2 \) through a clump, but \( H_2 \) exists to much lower extinctions.

The relative amount of CO and \( H_2 \) is set by the distribution of column densities in the ISM.

Maloney & Black (1988), Bolatto et al. (1999), Röllig et al. (2006)
Observations

HST imaging of the starburst in NGC 1569

P. Anders
Real Molecular Clouds

- Self similar
- Chaotic
- Fractal
- Complex
- But GMCs obey simple scaling relations (Larson 1979, 1981; Solomon et al. 1987)

Jackson et al. (2006)

$^{13}\text{CO} \, 1-0$

GRS datacube at $l=24^\circ$

$659\times0.2 \text{ km/s channels}$

$2.2^\circ \times 2^\circ \text{ field}$
The Size-Line Width Relation in Galaxies

Dwarfs fairly consistent with both Milky Way and local group spirals:
- for $\sigma \sim R^{0.5}$, $\Sigma_{H_2} \sim 85 \, M_\odot/pc^2$

Worst outliers (factor $\sim 2$): small clouds in SMC:
- low surface density?
- increased B-field?
  (e.g. Bot+ 07)
- clouds not virialized?

Main conclusion: broad agreement in the properties of CO-emitting regions

CPROPS methodology:
Rosolowsky & Leroy (2006)

Bolatto, Leroy, et al. (2008); see also Heyer et al. (2009), Blitz et al. (2007), and talk by Annie Hughes, poster by Erik Muller
The CO-to-H₂ Conversion Factor

Ratio of virial mass to CO luminosity vs. metallicity.

- $X_{CO}$ for virialized clouds.

No strong trend.

SMC completely compatible with MW clouds and Solomon (0.8) slope...

- i.e., $M_{vir}/L_{CO} \sim L_{CO}^{-0.2}$

Bolatto, Leroy, et al. (2008); talk by Karin Sandstrom
The SMC in the midIR

[SIII] 33.5um = Blue
H2 S(0) 28um = Green
UIB 11.3um = Red
3.6 um = Gray
Near-IR H$_2$ imaging

N159 in the LMC

H$_2$ pointings over CO
(Pak et al. 1998)

30 Doradus in the LMC

Rubio et al. (in prep.)
Using dust to trace $H_2$

CO is faint at low metallicities. FIR dust emission offers another view.

Traces the total gas (HI + H2) column.

In the Galaxy, matches Gamma Ray and CO results well.

Early IRAS analysis suggests very large Xco in the Magellanic Clouds (Israel 1997)

Method:

\[ \Sigma_{H_2} = (\Sigma_{\text{dust}} \times \text{GDR}) - \Sigma_{\text{HI}} \]

Estimate the dust surface density using FIR emission (need two bands to make a temperature estimate).

Measure the gas-to-dust ratio from the ratio of dust to atomic gas away from the molecular line emission but near enough to calibrate out galactic variations.

From 21 cm observations, the distribution of atomic gas is known.
Dust emission at 24, 70, and 160 μm from the SMC:
SMC-SAGE (PI: K. Gordon)+S3MC (Bolatto+ 07)
HERITAGE LMC
IRAC+MIPS+SPIRE (3.6, 24, 350)
image

"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

© Sidney Harris
Imaging of extended molecular envelopes

CO 2-1

H$_2$ from dust

Leroy, Bolatto, et al. (2009)
• Bright CO emission is found at $A_v \geq 2$

• Below $A_v \leq 1$, CO emission is extremely weak

• $A_v = 1$ implies $N(H) \sim 10^{22} \text{ cm}^{-2}$

• Clouds are $\sim 50\%$ more extended than their CO emission

Leroy, Bolatto, et al. (2009)
Low metallicity and the star formation laws

- Low metallicity local dwarf galaxies and outer galaxy disks are some of the most discrepant objects when placed on the molecular star formation law.
- Is this the result of imperfect estimates of $H_2$ surface densities?
- In Leroy et al. (2007) we applied the “dust” method to the SMC and showed that $H_2$ is more abundant than shown by CO.
**Results from recent modeling**

Simulations of time-dependent chemistry in a turbulent box, illuminated by UV, probing a range of metallicities

- $H_2$ abundance is mostly time dependent, very insensitive to photodissociation
- CO forms quickly, but its abundance is set primarily by photodissociation
- Therefore: $X_{CO}$ depends mostly on $A_V$, and only indirectly (through the dust-to-gas ratio) on metallicity
- Corollary: $X_{CO}$ is due to the combined effect of the $N(H)$ PDF and the DGR($Z$)

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**Graphs:**

- Left: Log (CO column density / cm$^{-2}$) vs. $z$ (pc) and $y$ (pc)
- Right: $X_{CO,est}$ [cm$^{-2}$ K$^{-1}$ km$^{-1}$ s$^{-1}$] vs. Mean visual extinction

*Glover & Mac Low (2010, astro-ph)*

*Poster by Rodrigo Herrera*
Using dust to study $\text{H}_2$ throughout the Local Group

- Obtain $\alpha$ and GDR by minimizing
  
  $$\alpha I_{\text{CO}} + \Sigma_{\text{HI}} - \text{GDR} \Sigma_{\text{dust}}$$

Leroy et al. (in prep.)
Colder dust modeling at longer wavelengths

LABOCA 870 um bolometer mapping of the South West region of the SMC (also Rubio et al. 2004, Bot et al. 2007)

Bot et al. (submitted)
Long wavelength Rayleigh-Jeans excess is present in both LMC and SMC

“Exotic” dust properties? (Meny et al. 2007; Boudet et al. 2005)

Very cold dust: requires huge dust mass (likely disallowed by mass constraints)

Out of equilibrium VSG dust emission? (Draine & Anderson 1985; Draine & Li 2001)

Israel & Raban (in prep.), also forthcoming
Herschel paper by Gordon et al.
See also Galliano et al. (2005); Bolatto et al. (2000)
The Star Formation Law

CTIO emission line imaging of the SMC (OIII, SII, Hα)

C. Smith, F. Winkler, & the MCELS team
Fraction of obscured SF according to the Calzetti et al. (2007) calibration is localized and small: we use Hα+24 um but Hα dominates
The $H_2$ Schmidt law in the SMC

The SMC, at $Z \sim 0.2 Z_\odot$ and 10 pc resolution, logarithmic contours

$\Sigma_{\text{SFR}}$ (M$_\odot$ yr$^{-1}$ kpc$^{-2}$)

$\Sigma_{H_2}$ (M$_\odot$ pc$^{-2}$)

4$\mu$m

Normal spirals
Bigiel et al. (2008)

log $\Sigma_{H_2}$ [M$_\odot$ pc$^{-2}$]
The total gas Schmidt law in the SMC

KMT09: Krumholz, McKee, & Tumlinson (2009)
Resolved molecular fraction and metallicity

Column density for the transition of atomic to molecular marches with metallicity

Krumholz, McKee, & Tumlinson (2009); see also Gnedin, Tassis, & Kravtsov (2009), Gnedin & Kravtsov (2010)
Summary: Molecules and metallicity

1. The CO-bright portions of molecular clouds are very similar everywhere, independent of metallicity
   - But less and less of a cloud is bright in CO as metallicity decreases

2. Use dust as a total gas tracer: low metallicity GMCs have extended translucent $H_2$ envelopes
   - In the SMC, most of the $H_2$ is in this regime, with $X \sim 30 \, X_{MW}$

3. The CO-to-$H_2$ conversion factor is a function of $N(H_2)$, and of metallicity through the dust-to-gas ratio
   - But keep in mind that $H_2$ is not coextensive with CO...

4. Based on the SMC, the molecular Star Formation Law is independent of metallicity
   - The total gas SFL and the molecular fraction show the metallicity effects
Abdo et al. (2010)
FERMI γ-ray emissivity from pion decay in the LMC and HI contours