The Resolved Properties of Extragalactic Giant Molecular Clouds

... or ...

Connecting the Galactic and Extragalactic Scales of Star Formation

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NGC 604 in M33

R: CO 1.5"
G: HST Hα
B: HST V
Why GMCs are important:

They mediate the formation of stars from gas, one of the key drivers of galaxy evolution.

The conversion of gas to stars is at the core of structure formation the direct conversion takes place in GMCs.
Take home message:

The CO-bright portions of extragalactic giant molecular clouds are almost* identical to those of Galactic giant molecular clouds**.

But CO tells only part of the story, particularly in the Small Magellanic Cloud. Dust suggests extended reservoirs of H$_2$ untraced by CO at very low metallicity.

* Details matter.
** Claims verified for non-starburst galaxies only.
*** Past performance is not necessarily indicative of future results.
Background: GMC scaling relations in the MW

- Recognized by Larson 79, 81 and attributed to Kolmogorov turbulence.
- Today attributed to compressible, shock-dominated supersonic (Burger’s) turbulence.
- In Milky Way:
  \[ \sigma = 0.72 R_{pc}^{0.5} \text{ km/s} \]
- Coefficient related to surface density:
  \[ \Sigma = M/R^2 \sim \text{const} \]
- In Milky Way:
  \[ \Sigma \sim 170 \frac{M_{\text{surf}}}{pc^2} \]
- But see recent work by Heyer et al. (2008)!

```
Size [parsecs]
```

```
Line Width [km s^{-1}]
```

"Size-Line Width Relation"

Points: individual Galactic GMCs

Solomon+ 87
**Background: GMC scaling relations in the MW**

**Mass-Luminosity Relation**

- Luminosity-line width and luminosity-size relations yield mass-luminosity relation
- Milky Way: 
  \[ M_{\text{vir}} = 39 \ L_{\text{co}}^{0.8} \ M_{\text{sun}} \]
- Quasi-linearity gives rise to \( X_{\text{co}} \), the CO-to-\( H_2 \) conversion factor
- In the MW, virial, \( \gamma \)-ray, and dust continuum values of \( X_{\text{co}} \) are consistent

**Points:** individual Galactic GMCs

Solomon+ 87
What We Did…

Compiled new and literature observations of GMCs:

- BIMA, OVRO, PdBI, and SEST

- spatial resolution 7-120 pc.

- metallicity to ~ 1/5 to solar.

- two orders in galaxy mass.

Analyzed these data in a consistent manner:

- CPROPS (Rosolowsky & Leroy 06)

### TABLE 2
**Galaxy Properties**

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**Disk Galaxies**

| Milky Way | SB      | 0.008  | −21.4 | 8.7  | 8    |
| M31       | Sb      | 0.79   | −21.1 | 8.7  | 10   |
| M33       | Scd     | 0.84   | −18.9 | 8.4  | 9    |

“The Resolved Properties of Extragalactic GMCs”
Measuring Extragalactic GMC Properties

Comparing heterogeneous data sets among galaxies is made challenging by biases due to ...

Finite Sensitivity
“Tip of the iceberg in a sea of noise”

Finite Resolution
Other galaxies are very far away

An attempt to systematically correct for these biases: CPROPS (Rosolowsky & Leroy 06)
The Size-Line Width Relation in Galaxies

Milky Way
Solomon+ 87

Line Width [km s\(^{-1}\)]

Radius [parsecs]

Milky Way

Solomon+ 87
The Size-Line Width Relation in Galaxies

Radius [parsecs]

Line Width [km s\(^{-1}\)]

Milky Way

Local Group Spirals

Milky Way

Solomon+ 87

Local Group Spirals

M31 & M33

Rosolowsky+ 03, Rosolowsky 07
The Size-Line Width Relation in Galaxies

![Graph showing the size-line width relation in galaxies.]

- Milky Way
  - Solomon+ 87
- Local Group Spirals
  - M31 & M33
- Dwarfs outside the Local Group
  - NGC 1569, 2976, 3077, 4214, 4449, 4605
- Local Group dwarfs
  - IC 10, LMC, NGC 185, NGC 205
- SMC
  - N83, LIRSS6, LIRSS49

Taylor+ 99, Walter+ 01, 03; Leroy+ 06, Young+ 01; Bolatto+ 03, Rubio+ 93 (SEST K.P.)
The Size-Line Width Relation in Galaxies

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

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

Main conclusion: agreement in CO-based GMC props...

(recall o.o.m. discrepancies in integrated properties).

dwarf GMCs: $\sigma = 0.31 \, R_{\text{pc}}^{0.65} \text{ km/s}$
(recall M.W.: $\sigma = 0.72 \, R_{\text{pc}}^{0.5} \text{ km/s}$)

- Milky Way
- Local Group Spirals
- Distant Dwarfs
- Local Group Dwarfs
- SMC
Luminosity-Virial Mass Relation

(one version of other independent Larson’s Law)

We find $M_{\text{vir}} \sim L_{\text{CO}}$ ...
- Solomon (MW): $M_{\text{vir}} \sim L_{\text{CO}}^{0.8}$

CO-to-H$_2$ factor roughly as MW if GMCs are virialized...

SMC falls on Galactic line.

Other scaling relations:
- $L_{\text{CO}}$ vs. $R$
- $L_{\text{CO}}$ vs. $\sigma$
- $M_{\text{vir}}$ vs. $R$
follow from these two.
The CO-to-H$_2$ 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., $M_{vir}/L_{CO} \sim L_{CO}^{-0.2}$
Photoionization-regulated star formation?

Star forming clouds need similar extinctions at their centers to decouple from magnetic support and collapse (McKee 1989)

Theory predicts
\[ \sigma = 0.72 \left( \frac{A_v}{7.5} \delta_{gp} \right)^{0.5} R^{0.5} \]

Measurements show no evidence of that trend

Caveats: are we reaching the relevant scales? Is the prediction overly simplistic?
Recent developments: $\Sigma$ may not be constant

Heyer et al. (2008) using GRS survey
Background: A Different Way to Trace H$_2$

CO is expected to be biased at low z. FIR dust emission offers another view.

- Traces the total gas (HI + H$_2$) column.
- Probably better, at least ‘differently biased.’
- In the Galaxy, matches Gamma Ray and CO results well.
- In the SMC, IRAS suggests much more H$_2$ than seen from CO (Israel 1997).

Method:

\[ \Sigma_{H_2} = (\Sigma_{\text{dust}} \times DGR^{-1}) - \Sigma_{\text{HI}} \]

Estimate the dust surface density using FIR emission at 100 & 160 microns (need two bands to make a temperature estimate).

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

From the beautiful ATCA+Parkes HI map by Stanimirovic et al. (1999), 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)
The Spitzer view of H\textsubscript{2} in the SMC at 70 pc

Use 100 and 160 um to model \( \tau_{\text{dust}} \)

Use \( \tau_{\text{dust}} \sim N(\text{HI}) + 2N(\text{H}_2) \)

Determine DGR locally

\( M_{\text{H}_2} \sim 3 \times 10^7 \ M_{\odot} \) total molecular mass, compared to \( M_{\text{HI}} \sim 2 \times 10^8 \ M_{\odot} \)

This means \( X_{\text{CO}} \sim 30-60 \) times Galactic!

Furthermore, \( \Sigma_{\text{FIR}} \sim 180 \ M_\odot/\text{pc}^2 \), while \( \Sigma_{\text{VIR}} \sim 45 \ M_\odot/\text{pc}^2 \)!

The \( \text{H}_2 \) we find places the SMC squarely into the molecular Schmidt law

Leroy, Bolatto, et al. (2007) using NANTEN CO
What happens at higher resolution?

We work out a “VSG-corrected” emissivity in the large scales, and assume it in the small scales.

We map the CO and H$_2$ distribution at 15 pc scales.

CO emission is seen only at $A_v > 1.6$, $\Sigma \sim 350$ $M_\odot$/pc$^2$.

How do we put together this picture with the kinematic studies?

Leroy, Bolatto, et al. (2008, in prep.)
Metallicity and Cloud Structure in the SMC

CO-emitting GMCs are just the peaks of the $H_2$ distribution in the SMC.

GMC internal kinematics (and so $M_{\text{vir}}$) sample only the potential of this CO-emitting volume.

- hence low $X_{CO}$ from CO.

There are large envelopes containing most of the mass surrounding these peaks

- hence large mass of $H_2$ (FIR).

This gas lacks the extinction to form CO.

- hence large $H_2$ (FIR) / CO

Israel et al. (1987); Maloney & Black (1988); Elmegreen (1989); Rubio et al. (1993)
Metallicity and Cloud Structure in the SMC

Consistent with cloud-cloud dispersion (e.g., NANTEN virial mass results)

In MW parts of clouds follow Larson’s Laws
Heyer & Brunt 04, Rosolowsky+ 08, Wong+ 08

Requires \( H_2 \) self-shielding to be important at metallicity \( \sim 1/5 \) solar

Low-\(A_V\), CO-free gas somehow participates in star formation... but in local (MW) clouds SF also restricted to densest parts of clouds.

Israel et al. (1987); Maloney & Black (1988); Elmegreen (1989); Rubio et al. (1993)
Summary

- The CO-bright parts of extragalactic GMCs show remarkable similarities:
  - Larson relations are universal
  - Surface densities are similar to MW ($\Sigma \sim 85 \ M_{\odot}/\text{pc}^2$)
  - Virial mass-CO Luminosity relation is similar too:
    $X_{\text{CO}}$ approximately Galactic inside resolved GMCs

- Nevertheless metallicity plays a role:
  large, low-$A_V$ molecular envelopes are invisible in CO in the SMC

- We really need ALMA to expand these studies beyond the immediate vicinity of the Milky Way
  - Clouds in starbursts and mergers?
  - The outskirts of galaxies?
  - Dense portions of molecular clouds?
  - Submm dust emission at high resolution?
A systematic sampling of the blue sequence