GMC Populations of Nearby Galaxies

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CANON: Jin Koda, Jen Donovan-Meyer, M31: Andreas Schruba
MAGMA: Tony Wong, Juergen Ott
Motivation

Milky Way’s molecular mass is $\sim 2 \times 10^9 \, M_\odot$

$n \sim 100 \, \text{cm}^{-3} \implies t_{\text{ff}} \sim 4 \times 10^6 \, \text{yr} \implies \text{SFR} \sim 500 \, M_\odot \, \text{yr}^{-1}$

Observed SFR is 0.7 to 1.5 $\, M_\odot \, \text{yr}^{-1}$

Explanation depends on whether GMCs are:

- bound + long-lived
- unbound + short-lived
- collapsing + short-lived

- e.g. Krumholz & McKee (2005)
- e.g. Dobbs et al (2011)
- e.g. (Ballesteros-Paredes et al. (2011)
A Resolved Extragalactic SF ‘Law’

stars form from molecular gas with a constant depletion time of \(~2\) Gyr in nearby disk galaxies

**Log (Molecular Gas Surface Density)** vs. **Log (SFR Surface Density)**

- **nearby galaxies**
- **starburst, high z**

**Compilation by Hodge et al. (2014)**

- Leroy et al. 2013
- Kennicutt 1998
- Bouche et al. 2007
- Bothwell et al. 2009
- Tacconi et al. 2013
- Daddi et al. 2010
- Freundlich et al. 2013
- Sharon et al. 2013
- Rawle et al. 2014
- This work (GN20)

**dN/dM**

- **slope = -1.5**

**Mass**

- **slope = 0.5**

**Size**

**Velocity Dispersion**

- Solomon et al. (1987)
Do the properties of a GMC population depend on host galaxy properties?

Do galaxy properties & processes influence GMC formation and evolution?

Do GMC properties matter for star formation (on galactic scales)?

NGC253: Leroy
M31: Schruba
NGC4526: Utomo
CANON: Donovan-Meyer
M33: Druard, Gratier, Braine
NGC6822: Gratier
IC342: Hirota
M83: Hirota
Are GMC Properties Universal?
GMCs identified on the basis of their CO emission exhibit remarkably uniform properties from galaxy to galaxy...

“GMCs identified on the basis of their CO emission exhibit remarkably uniform properties from galaxy to galaxy…”

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Some observational evidence that GMC dynamical properties (e.g. mass, linewidth) may depend on galactic environment

IC342
- Hirota ea (2011)

LMC
- Hughes ea (2010)

CARMA-STING
- Wong ea (2013)

+ clear evidence for mass evolution through spiral arms

e.g. Koda ea (2009), Egusa ea (2011)

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Size-linewidth relation: M51, M33, LMC

Decomposition applied to CO data cubes with their original spatial and spectral resolution.

Data points cluster around the resolution limits.

Scaling relations obtained from composite samples must be interpreted with caution: beware observational bias.

this ‘correlation’ largely due to resolution effects.
Size-linewidth relation: M51, M33, LMC

Hughes et al (2013b)

The 'correlation' largely due to resolution effects in intrinsic.

At fixed size, M51 clouds still have higher $\sigma$. 

This image shows a scatter plot with two subplots: one labeled 'intrinsic' and the other 'matched'. The x-axis represents the logarithm of the radius in parsecs ($\log(R/\text{pc})$), and the y-axis represents the logarithm of the velocity dispersion ($\log(\sigma/\text{km/s})$). The plot includes data points for M51, M33, and LMC, with different symbols indicating different regions of the spiral arm.
Within M51, slope and normalisation of size-luminosity relationship varies. 

\(<\Sigma>\) at fixed scale also varies between galaxies.

difference in \(<\Sigma>\) between spiral and dwarf galaxies (factor of ~10) exceeds \(X_{\text{CO}}\) variations (factor of ~2 to 3)

Hughes et al (2013b)
Extragalactic Larson Relations at 50pc

<σ>/R and Σ of GMCs vary with galactic environment

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A consequence of external pressure?

\[ \frac{M}{R^2} \approx 190 \pm 90 \left( \frac{P_e}{10^4 \, k_B \, \text{cm}^{-3} \, \text{K}} \right)^{1/2} M_\odot \, \text{pc}^{-2}, \]

\[ \frac{c}{R^{1/2}} \approx 0.4 \pm 0.1 \left( \frac{P_e}{10^4 \, k_B \, \text{cm}^{-3} \, \text{K}} \right)^{1/4} \, \text{km} \, \text{s}^{-1} \, \text{pc}^{-1/2} \]

e.g. Elmegreen (1989)

\[ P_{\text{ext}} = \frac{\pi G}{2} \Sigma_g \left( \Sigma_g + \frac{\sigma_g}{\sigma_*} \Sigma_* \right) \]

if \( P_{\text{int}} \sim P_{\text{ext}} \), environment more likely to influence cloud stability, dense gas mass function, star formation activity, GMC evolution...

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How is Molecular Gas in Galaxies Distributed?
GMC Mass Distributions: Motivations

- diagnostic of GMC formation & destruction processes
- potential link to core mass function and cluster IMF
- in inner MW, $\gamma = -1.5 \Rightarrow$ GMCs dominate total $H_2$ mass

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PAWS Survey of M51: Dynamical environments defined in Colombo et al (2014)
GMC Mass Spectra: M51 environments

- RING: log(N(m>M)/[kpc^2]) = -1.6
- ARM outside CR: log(N(m>M)/[kpc^2]) = -1.8
- UP: log(N(m>M)/[kpc^2]) = -2.4
- BAR: log(N(m>M)/[kpc^2]) = -1.3
- ARM inside CR: log(N(m>M)/[kpc^2]) = -1.8
- DOWN: log(N(m>M)/[kpc^2]) = -2.6

Colombo et al (2014)
GMC & Young Cluster Properties

Mass Function Slope

MF slope (clusters)

MF slope (GMCs)

Maximum (P95) Mass

Log(Max Cluster Mass)

log(Max GMC Mass)

Hughes et al (2013a)

- M51 overall
- bar
- arm1
- ring
- arm1 out
- arm1 in
- arm2
- interarm
- downstream
- upstream
GMC Mass Spectra: Nearby Galaxies

log (GMC Mass/[M_☉])

simple power law is insufficient for most galaxies

GMC mass spectra are steeper in diffuse environments

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shape of GMC mass distribution is not universal: slope and turnover mass increase in more massive systems
Do GMC properties matter for star formation (on galactic scales)?
Star Formation: Theory

*In star formation theory, the SFR depends on the properties of the parent cloud*

- cloud properties act as the boundary conditions for small scale star formation
- turbulent cloud properties set the density distribution
- Mach number sets the width of density distribution

Star Formation in Local Clouds

In local clouds, SFR relates to high density gas, not total $H_2$

- YSOs found in regions of high column density and extinction
- Actively SF clouds show excess amounts of high extinction material
- SF appears closely associated with dense filamentary substructure


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Extragalactic Star Formation

SFR-per-$H_2$ varies systematically on large scales in local galaxies

- High SFR/CO in galaxy centres, luminous starbursts, low-metallicity dwarfs
- Low SFR/CO in ETGs
- SFR/CO shows variations with local gas kinematics, galaxy morphology and metallicity


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For simplicity, we write:

- TIR/CO: overall SFE in H$_2$
- HCN/CO: dense gas fraction
- TIR/HCN: SFE of dense gas

Measure TIR/CO, SFR/HCN, or HCN/CO ratio in a ~kpc aperture that is small enough to roughly isolate local conditions.

Integration over a ~kpc area is needed to capture the time-cycling of gas and stars.
Within the ~kpc aperture, measure the typical cloud-scale properties of the molecular gas, e.g. mass-weighted surface density, velocity dispersion (Mach number), and gravitational boundedness.
Underlying GMC Properties Matter

Within the PAWS field-of-view, the ability of the ISM to form stars (IR/CO) correlates with the self-gravity of the gas at cloud (50 pc) scales – gas that is more bound appears better at forming stars.
Underlying GMC Properties Matter

Within the PAWS field-of-view, the average small scale surface density within a kpc region correlates with the apparent fraction of the molecular gas mass that is dense.

HCN-to-CO at 1kpc

~ dense gas fraction

Leroy, Hughes, Schinnerer, Bigiel (in prep)
Underlying GMC Properties Matter

But higher cloud-scale surface densities are associated with lower ratios of star formation per unit dense gas! I.e. dense gas is worse at forming stars as overall ISM density increases.

\[ \text{IR-to-HCN at 1kpc} \sim \text{SFE in dense gas} \]

Leroy, Hughes, Schinnerer, Bigiel (in prep)

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Summary

GMC physical properties and mass distributions vary with environment, both within and among galaxies.

More massive systems tend to have denser, more turbulent GMCs, and tend to build more massive GMCs.

In M51, relations between star formation, molecular gas and dense gas are qualitatively consistent with a “whole cloud” view in which star formation occurs in local overdensities (rather than a universal density threshold).