THE EFFECT OF METALLICITY ON MOLECULAR GAS AND STAR FORMATION IN THE MAGELLANIC CLOUDS

Hannah Krug’s photo of the Southern Sky from Chile

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1. Molecular Gas and Star Formation in the LMC
   - New H$_2$ map using Dust instead of CO
   - CNM and WNM important for star formation model

2. Heating and Cooling of H$_2$ in the SMC
   - Physical conditions of warm H$_2$

3. Revealing the structure of “CO-faint” H$_2$ in the SMC using [CII]
   - Ratio of [CII] to $^{12}$CO in N22
How does star formation efficiency depend on galaxy mass and metallicity?

SSFR = Σ_{SFR}/Σ_{(CO,H2,total)} = τ_{dep}^{-1}

Krumholz et al. (2011)

(high-z galaxies; Genzel et al. 2012)
CO traces less $\text{H}_2$ at lower metallicity

$\nabla_{\text{UV}}$ (dissociating radiation field)

diffuse (atomic, ionized)

high metallicity  \hspace{2cm} low metallicity
Dust can trace $\text{H}_2$ at low metallicity.
Fit $T_d$ to HERITAGE data and map $\tau_{160\mu m}$

$T_d$ fit modified blackbody with $\beta = 1.8$

$T_{160}$ proportional to $M_{dust}$
Mapping \( \text{H}_2 \) using dust emission

\[
\sum_{\text{gas}} = \sum_{\text{HI}} + \sum_{\text{H}_2}
\]

\[
\sum_{\text{dust}} \propto \tau_{160\,\mu\text{m}}
\]

\[
\sum_{\text{gas}} = \delta_{\text{GDR}} \times \sum_{\text{dust}}
\]

\[
\sum_{\text{H}_2} = \left( \delta_{\text{GDR}} \times \tau_{160\,\mu\text{m}} \right) - \sum_{\text{HI}}
\]

Previous Work:
MCs – Israel (1997); MW – Dame+ (2001);
SMC – Leroy+ (2007); Leroy et al. (2009); Bolatto et al. (2011)
*new* dust-based $H_2$

SFR (SHASSA $H\alpha$)
(Gaustad et al. 2001)

ATCA+Parkes HI
(Kim et al. 2001)

ATCA+Parkes HI
(Kim et al. 2001)

$M(H_2) \sim 8 \times 10^7 M_{\text{sun}} \sim 20\% M(\text{HI})$
How galaxies convert molecular gas to stars does not vary strongly with metallicity.

**LMC**

\[ Z' \sim 1/2 \text{ Solar} \]

\[ \tau_{\text{dep}} (200 \ \text{pc}) = 1.6 \ \text{Gyr} \]
Different approximations of the ISM: pressure-driven vs. shielding

Ostriker, McKee, & Leroy (2010) (OML10)

Krumholz, McKee, & Tumlinson (2009) (KMT09)

~200 pc
How well do the models predict the fraction of molecular gas?

Ostriker, McKee, & Leroy (2010)  
(KML10)

Krumholz, McKee, & Tumlinson (2009)  
(KMT09)

$\Sigma_{H_2}/\Sigma_{H_1}$ vs. $\Sigma_{\text{gas}}$ (M$_\odot$ pc$^{-2}$)
How about predicting star formation rate based on total gas?

Ostriker, McKee, & Leroy (2010)

(KML10)

Krumholz, McKee, & Tumlinson (2009)

(KMT09)
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Spitzer Spectroscopic Survey of the SMC (S$^4$MC)

(Sandstrom et al. 2012)
Fitting line emission in the IRS S$^4$MC data

SW Bar #3

pixel [57,57]

Full Fit
PAH Features
Emission Lines
Dust Continuum
Mapping H$_{2}$ line emission in the SMC

N83/N84

$\Sigma_{N83/N84}$
Modeling H$_2$ line emission

Excitation Diagram
(example pixel)

1. $N_{u,2}/g_{u,2} = \frac{N_{\text{warm}}}{Z(T_{\text{warm}})} \exp\left(-\frac{E_{u,2}}{kT_{\text{warm}}}\right)$, $N_{u,4}/g_{u,4} = \frac{N_{\text{warm}}}{Z(T_{\text{warm}})} \exp\left(-\frac{E_{u,4}}{kT_{\text{warm}}}\right)$.

2. $N_{u,0}/g_{u,0} = \frac{N_{\text{cool}}}{Z(T_{\text{cool}})} \exp\left(-\frac{E_{u,0}}{kT_{\text{cool}}}\right)$, $T_{\text{cool}} = 100$ K.

3. $N_{u,1}/g_{u,1} = \frac{N_{\text{cool}}}{Z(T_{\text{cool}})} \exp\left(-\frac{E_{u,1}}{kT_{\text{cool}}}\right) + \text{OPR} \times \frac{N_{\text{warm}}}{Z(T_{\text{warm}})} \exp\left(-\frac{E_{u,1}}{kT_{\text{warm}}}\right)$.

Excitation Diagram (example pixel)
Physical conditions of warm H$_2$ in the SMC

\[ f(H_2 > 100K) \sim 10 - 20\% \]
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**Herschel** Spectroscopic Survey of the SMC (HS³)

Insets: “CO–dark” H$_2$ map (Roman–Duval et al. in prep) with CO contours

**HERITAGE** 100µm

SMC–SAGE 24µm

MCELS Hα

(PI: Bolatto)
Mapping the structure of “CO–dark” H$_2$ gas

- Anchor the dust–based H$_2$ estimates
- Map detailed structure
Preliminary results: Comparing $I_{\text{[CII]}}/I_{\text{CO}}$ in N22 to IC 10

<table>
<thead>
<tr>
<th>Position</th>
<th>$I_{\text{[CII]}}/I_{\text{CO}}$ $(10^4)$</th>
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<tbody>
<tr>
<td>IC 10A</td>
<td>1.4</td>
</tr>
<tr>
<td>IC 10B</td>
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<tr>
<td>IC 10C</td>
<td>2.0</td>
</tr>
<tr>
<td>IC 10D</td>
<td>&gt; 8.7</td>
</tr>
<tr>
<td>IC 10E</td>
<td>8.7</td>
</tr>
</tbody>
</table>

SUST CO(1–0) [1, 2, 3 K]
This talk in a nutshell

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Extra Slides...
$T_d$ and $\beta$ across the LMC
Map $H_2$ using dust emission

$$\Sigma_{\text{gas}} = \Sigma_{\text{HI}} + \Sigma_{H_2}$$

$$\Sigma_{\text{dust}} \propto \tau_{160 \mu m}$$

$$\Sigma_{\text{gas}} = \delta_{\text{GDR}} \times \Sigma_{\text{dust}}$$

Previous Work:
MCs – Israel (1997); MW – Dame+ (2001);
SMC – Leroy+ (2007); Leroy et al. (2009); Bolatto et al. (2011)
GDR map smoothed to 500 pc ($\beta = 1.8$)

2 x MW cirrus value

MW cirrus value
Regional variations in the GDR and $N_{\text{HI}}$ offset
Regional variations in the GDR and $N_{\text{HI}}$ offset
Column density map at ∼50 pc resolution produced by modeling the dust continuum emission from Herschel observations from HERITAGE (Meixner et al.). The white contour shows the estimated sensitivity level of $N_{\text{H}_2} = 2 \times 10^{21}$ cm$^{-2}$.

Extinction-corrected $\Sigma_{\text{SFR}}$ from H$\alpha$ and SMC SAGE $\mu$m with the H$_2$ map overlaid with contour levels at $N_{\text{H}_2} = 2 \times 10^{21}$ cm$^{-2}$.

The SHASSA H$\alpha$ image was further background subtracted by fitting a polynomial to the median of the background value along the y image axis; the H$\alpha$ background appears to come from foreground diffuse Galactic emission and the average change from the background subtraction was ∼40%. The star formation is generally correlated with the molecular gas, but at high resolution, there is star formation without molecular gas, molecular gas with little star formation, and diffuse H$\alpha$ emission throughout much of the disk.
Constant SSFR with decreasing metallicity

Krumholz et al. (2011)
Fraction of molecular gas as a function of metallicity

**LMC**

**SMC**

20 pc resolution
200 pc resolution
1 kpc resolution

KMT09 curve overestimates the molecular-to-atomic ratio by a factor of two to three. In the SMC, the atomic gas is not as clumpy as the dark matter density in the SMC. The original OML10 prediction for the velocity range between 120–180 km s\(^{-1}\) is due to the fact that the self-gravity of the gas dominates over the stellar plus dark matter component. The wealth of atomic gas into molecular gas, particularly given the diffuse gas, lowers the predicted surface density ratio of gas in gravitationally bound complexes to the predicted gas mass of the galaxy. We find that this exercise is representative of the disk of the galaxy. We note that since the scaling is linear, this result is insensitive to uncertainty in inclination or other aspects of the SMC's geometry. By contrast, the total gas star formation law is offset to a low molecular fraction in DLAs. More recently, Krumholz & Chen indeed suggest that part of the explanation may be the low abundance of CO (an important gas coolant in dense molecular cores) could make it difficult for cores to collapse and resulting in lower SFE and longer timescales for consuming the energy of gravitational contraction, slowing their collapse.
"Star Formation Law" as a function of metallicity

**Figure 11** shows the SFR predicted by OML10 as a function of the specific star formation rate in GBCs, OML10p, the gravitationally-bound component is measured by Dickey et al. (2000). Compared to OML10h, the gravitationally bound gas at low metallicity (as for the SMC), the SFR expected in OML10p at a fixed gas surface density is significantly higher than in OML10h. Similarly, OML10h and OML10p have the same level of SFR activity but also the slope of the star formation law. It should be noted that the specific star formation rate in GBCs is assumed to vary as OML10ph (see below) have the same characteristic gas and dust continuum observations (Bolatto et al. 1999) distributions (Figure 2). The depletion time scale for the SMC as a whole is shorter, due to the higher abundance of gravitationally-bound H\(_2\). In the context of OML10, all of the gas in the gravitationally-bound component, the SFR expected in OML10p at a fixed gas surface density is significantly higher than in OML10h. Similarly, OML10h and OML10p have the same level of SFR activity but also the slope of the star formation law.
Fig. 7.— Left: The OML10 models for the two bounds on the density of stars and dark matter given the two dark matter profiles with the low estimate from the HI rotation curve, and the high from HI rotation curve — carbon stars. Right: Effect of decreasing the depletion time in the model.
Results from modeling H$_2$ line emission
Heating and cooling of H$_2$ in the SMC
FTS Spectra!

Star forming region N22 in SMC

CO 4–3  CO 5–4  CO 6–5  CO 7–6  CO 8–7  [CI] 1–0  [CI] 2–1  [NII] 1–0

Flux (W m^2 Hz^{-1} s^{-1})

Frequency (GHz)