Exploring ISM and Star Formation Physics in the LMC and SMC in the SOFIA Era

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The complexity of the ISM

- Multi-Physics
- Multi-Phase
- Confusion/beam dilution
- Multi-Scale (complex geometries)
- Biased tracers (Excitation, chemistry)
- Distance ambiguity

LMC R136
Hubble - NASA
Star Formation Relation

Complex ISM physics of SF and feedback lead to remarkably universal SF relation in dense gas

Krumholz+12
The Magellanic Clouds as laboratories for ISM/SF physics

- LMC/SMC (currently) only 2 galaxies where ISM processes can be resolved at the level of individual stars and clouds while also getting the broad spatial coverage needed understand the ISM on global scales
  - Providing context to ISM Processes is much easier there than in the MW
  - Sub-GMC-scale studies of SF relation possible (See Talk by B. Ochsendorf)

- LMC has face-on geometry
  - HI disk is ~120 pc thick (Elmegreen+2001)
  - SMC elongated along l.o.s with complex velocity structure

- Metallicity of LMC (0.5 solar) and SMC (0.2 solar) span metallicity of galaxies at the peak of cosmic star formation
Herschel 250 mic
Herschel 100+160 mic
Spitzer 24+70 mic
ATCA HI 21 cm
MAGMA CO
MCELLS Hα

Coverage: 8x8 deg²
Resolution: 15 pc (limited by HI)
Herschel 250 mic
Herschel 100+160 mic
Spitzer 24+70 mic
ATCA HI 21 cm
NANTEN CO
SHASSA Hα

SMC

Coverage:
40deg²

Resolution: 45 pc
(limited by CO)
Dust maps

Dust modeling built in a probabilistic SED fitting framework yields dust surface density and temperature maps (Gordon+2014, Roman-Duval+2014)
Outline

• ISM structure is a determinant factor in the SF process
  – What are the effects of metallicity on the structure of the ISM?

• How can we trace the ISM at low (and solar) metallicity?

• What the effects of metallicity on the SF process?

• How do dust properties change at low metallicity and how does this affect our understanding of the ISM and SF?
Effects of Metallicity on ISM structure
Effects of metallicity on ISM structure and composition: CO distribution

- Dust abundance and shielding is reduced
  - Higher gas column density required to form CO
  - Filling factor of dense ISM reduced

From Wolfire+2010
Effects of metallicity on CO and H$_2$ structure

Simulations from Glover & Clark 2012

SOFIA Meeting - October 20, 2016
Small Filling Factor of dense ISM

Lack of dust shielding leads to small filling factor of CO gas in LMC and SMC

$$M(\text{HI}) = 4 \times 10^8 \, M_\odot$$
$$M^{\text{CO}}(\text{H}_2) = 10^7 \, M_\odot$$
$$M^{\text{dust}}(\text{H}_2) = (1-6) \times 10^7 \, M_\odot$$

$$M(\text{HI}) = 3.5 \times 10^8 \, M_\odot$$
$$M^{\text{CO}}(\text{H}_2) = (0.07-0.4) \times 10^7 \, M_\odot$$
$$M^{\text{dust}}(\text{H}_2) = (0.2-2) \times 10^7 \, M_\odot$$

Roman-Duval+2014, Jameson+2016

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Comparison to M51

CO from PAWS (Schinnerer+2013, PdBI)

\[ M(\text{HI}) = 2.8 \times 10^9 \, M_\odot \]
\[ M^{\text{CO}}(\text{H}_2) = 6.2 \times 10^9 M_\odot \]
Characterizing CO structure at low metallicity with ALMA

• Cycle 4 ALMA program to map 12CO, 13CO, C18O 1-0 and 2-1
  – 6 regions in LMC and SMC spanning range of $G_0$
• Tony Wong has another program to map 4 more regions
Characterizing CO structure at low metallicity with ALMA

Follow up with SOFIA in CII?
Tracing the low-metallicity ISM with FIR spectroscopy
Dust-based $\text{H}_2$ maps

- The CO-dark $\text{H}_2$ can be traced from its dust emission
  - $\Sigma(\text{H}_2) = G/D \times \Sigma_{\text{dust}} - \Sigma(\text{HI})$ (See Jameson+2016)
  - Large systematic uncertainties ($x2-3$) due to degeneracy between dust mass/emissivity and G/D uncertainty and variations

From Jameson+2016
SOFIA can observe [CII] in the LMC

- Okada+2015 mapped N159 (LMC) in [CII] with GREAT
- [CII] more extended than CO 3-2 (black contours, from APEX)
SOFIA can observe [CII] in the LMC

- Okado+2015 mapped N159 (LMC) in [CII] with GREAT
- [CII] more extended than CO 3-2 (black contours, from APEX)
[CII] velocity structure in N159

[CII] spectrally more extended than CO, CI
Characterizing the ISM in 30-Dor

- Wealth of FIR data in LMC 30-Doradus (Chevance+2016)
  - Herschel PACS, SPIRE/FTS, Spitzer/IRS, Mopra, Aste
Tracing H$_2$ in 30-Dor with [CII]

- PDR modeling provides density distribution and radiation field
- CII originates in hot, dense molecular gas
Herschel Spectroscopic Survey of the SMC (HS$^3$)

PI: Bolatto; Jameson+ in prep

PACS 160 $\mu$m
MIPS 24 $\mu$m
MCELS Hα
Results from HS³

- [CII] and [OI] are detected throughout the regions
“The GREAT [CII] Account of the Low-Metallicity ISM in the SMC”

PI Herrera-Camus (MPE)

Herrera-Camus, in prep
How much $[\text{CII}]$ comes from ionized gas?

- $[\text{CII}]$ emission originates both in ionized and atomic/molecular gas
- $[\text{NII}]/[\text{CII}]$ ratios can help quantify fraction of $[\text{CII}]$ from ionized gas

Okado+2015 (N159, GREAT): 15% of $[\text{CII}]$

Jameson+2016 (SMC-SWBar, Herschel): 5% of $[\text{CII}]$ emission from ionized gas
Does [CII] trace atomic or molecular gas?

- [CII] emission originates both in ionized and atomic/molecular gas
- \([\text{OI}]/[\text{CII}]\) ratios can help quantify fraction of [CII] from atomic gas

\[ [\text{OI}]/[\text{CII}] \sim 0.3 \]
Does [CII] trace atomic or molecular gas?

Cooling rates from Wolfire+ in prep
Evidence that the [CII] emission originates in molecular gas

SOFIA GREAT [CII] 158 µm line for one pointing (#7) in SWBarN

Jameson+, in prep
SOFIA in LMC/SMC

Large systematic uncertainties on dust emission-based molecular gas

→ SOFIA/(up)GREAT in more regions!
Tracing the ISM at sub-cloud scales with extinction
Extinction mapping with HST

- High-resolution, deep extinction mapping with multi-band HST imaging (WFC3+ACS)
  - Dalcanton+2013, Gordon+2016
- Fit SED toward each star with dust+stellar atmosphere model
Probing ISM structure with HST and ALMA

- Fit geometrical model to ensemble of individual $A_V$ toward each stars (Dalcanton+2013) to derive extinction maps
- Trace CO at similar resolution with ALMA

Pineda+2010 (Taurus)
Extinction from 2MASS

M31 (HST PHAT)
Dalcanton+2013
The Truth may not be so local anymore!
Effects of Metallicity on kpc-scale star formation relation
Effects of metallicity on SF timescales

- Trace H₂ from dust (FIR) or FIR fine structure line ([CII], [NII], [OI]) from SOFIA/Herschel
- Trace SF from MIR and Hα (or YSOs)
Effects of metallicity on SF timescales

- Molecular depletion times on 1 kpc scale in LMC and SMC (0.5 Gyr) are slightly shorter than in disk galaxies (2 Gyr), possibly indicating a recent burst in SF
- No clear dependence on metallicity

*Jameson+2016 (dust-based $H_2$)*

\[ \log \left[ \frac{\Sigma_{SFR}}{M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}} \right] \]

\[ \log \left[ \Sigma_{\text{mol}} (M_\odot \, \text{pc}^{-2}) \right] \]

\[ \log \left[ <\tau_{\text{dep, mol}}^\star> \right] \, [\text{yr}] \]

\[ \text{Metallicity} \, [12 + \log_{10} \text{O/H}] \]

\[ 8.0 \quad 8.2 \quad 8.4 \quad 8.6 \quad 8.8 \quad 9.0 \]

\[ 7.5 \quad 8.0 \quad 8.5 \quad 9.0 \]
SF timescales vs resolution

- LMC/SMC are the rare galaxies where we can estimate the effects of resolution on the SF relation.
- Variations of $\tau_{\text{dep}}$ and $\sigma(\tau_{\text{dep}})$ due to spatial separation of gas and SFR tracers and sampling of different evolutionary stages of SF (Kruijssen & Longmore 2014).

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**Graph:**

- Log (Median $\tau_{\text{dep, mol}}$ [yr]) vs Resolution [pc].
- Data points for LMC and SMC are shown.
- Error bars indicate uncertainty.

**Legend:**

- LMC
- SMC
- Average HERACLES
- LMC Fit ($\gamma = 0.43$)
- SMC Fit ($\gamma = 0.24$)
- Average HERACLES Fit ($\gamma = 0.5$)
- Uncorrelated ($\gamma = 1$)

**Source:**

Jameson+2016
Variations of Dust Properties with Metallicity: systematic uncertainties on gas mass estimates
Dust properties in the LMC and SMC

- Dust properties in LMC and SMC differ from MW
  - Extinction curves
  - Depletions
  - FIR SED (spectral emissivity index)
- Significantly affects radiative transfer, shielding, and therefore SF

Dust extinction curve differences (Gordon+2003)

\[ \frac{A(\lambda)}{AV} \]

\[ \lambda [\mu m] \]

MW \( R_V = 2 \)  
MW \( R_V = 5 \)  
SMC Bar  
SMC Average  
SMC Supershell  
LMC Average  
LMC Supershell  

\[ \text{Tchernyshyov+2015 (HST, FUSE)} \]
G/D in the LMC and SMC

- Dust-to-gas ratio increases non-linearly with metallicity?
  - LMC: G/D = 380 +/- 150
  - SMC: G/D = 1200 +/- 400

- Large systematic uncertainties on emission-based G/D affects ability to estimate H$_2$ in low-Z galaxies

Roman-Duval + 2014
Herschel HERITAGE key-project
PACS 100, 160 µm
SPIRE 250, 350, 500 µm
G/D vs Surface Density

- Dust-to-gas ratio variations with surface density (Roman-Duval+, in prep)
  - Obtained from stacked Planck data
  - Surface density range bridges ISM and CGM

- **WARNING:** Dust-based H$_2$ masses assume constant G/D!!!!
Metal Evolution and TrAnsport in the Large Magellanic Cloud (METAL)

- Systematic uncertainties on FIR dust emission-based G/D estimation is large (emissivity/mass degeneracy)
  - FIR emissivity environmental variations poorly constrained (factor of 2-3)
- FIR emission does not constrain dust composition
- Probe dust abundance and composition with HST UV absorption spectroscopy ($A_V < 1.2$)

![Graph showing emission spectra and Si II (1808) line]
Dust Composition and Size with METAL

METAL will constrain how dust abundance and composition varies with environment within the LMC and how it differs from the SMC and MW.
FIR emissivity mapping

- WFC3 images in UV-NIR will provide extinction maps
- Comparison to Herschel FIR emission will yield dust FIR emissivity

M31 (PHAT)
Gordon+2016
Arab+, in prep
What next?
PAH Properties in the LMC/SMC?

- Characterize 7.7 µm/11.3 µm with FORCAST spectroscopy?
  - Environmental dependence (radiation field, surface density)
- SMC has Spitzer/IRS spectroscopic observations, LMC more limited

**Smith+2008**
*Spitzer/IRS spectroscopy from SINGS survey (Kennicutt+2003)*

**Sandstrom+2010**
$q_{PAH} = 0.6\%$
PDRs with JWST

From Sheffer+2011

ESO/VISTA

HD37903

3'

NGC 2023
Southern Ridge

From Sheffer+2011

LH Pixel
4.46''
Dust and ices with JWST

JWST launch is 2 years away!

NIR-MIR spectral maps of molecular clouds to characterize dust composition, PAHs, ices...

NIRPSEC (H-gratings)
R = 2700

MIRI
R = 3000
This is not the end!

Thank you