Understanding the multi-phase structure and physical conditions of the ISM

A dominant reservoir of CO-dark molecular gas in 30 Doradus

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Galaxy formation in a cosmological context

Gas temperature: blue – green – red – white
Gas surface density: intensity
Vogelsberger et al. (2014)
Star formation and feedback in galaxy simulations

Jeffreson et al. (2020)

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Uncertainties on the physics of star formation and feedback

Different criteria for star-forming gas

Different feedback prescriptions

Hopkins et al. 2013

Keller & Kruijssen 2020

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Understanding the multi-phase structure and physical conditions of the ISM

- **Multi-wavelength** observations,

- In a **variety of environments**, 

- At **high spatial resolution**
Understanding the multi-phase structure and physical conditions of the ISM

- **Multi-wavelength** observations, [OI], [CII], [OIII], [NIII]
- In a **variety of environments**, 
- At **high spatial resolution**
Understanding the multi-phase structure and physical conditions of the ISM

- **Multi-wavelength** observations, \([\text{[O}I], \text{[C}II], \text{[O}III], \text{[N}III]\]
- In a **variety of environments**, Range of metallicities, densities, SF activity
- At **high spatial resolution**

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Understanding the multi-phase structure and physical conditions of the ISM

- **Multi-wavelength** observations, [OI], [CII], [OIII], [NIII]
- In a *variety of environments*, Range of metallicities, densities, SF activity
- At **high spatial resolution** Nearby galaxies

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Diagnostic of various phases in the ISM

Kennicutt et al. 2011
Diagnostic of various phases in the ISM

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Diagnostic of various phases in the ISM

Kennicutt et al. 2011
Structure of the ISM

Solar Metallicity

Madden et al. 2020

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Structure of the ISM

Solar Metallicty

Low Metallicity / High Radiation Field

CO, H₂

Madden et al. 2020

Aᵥ(C+/C) ~ 1
Aᵥ(C/CO) ~ 5

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Low metallicity nearby galaxies

LMC 30 Dor
- $Z = 1/2 \, Z_\odot$
- $D = 50$ kpc

IC10
- $Z = 1/3 \, Z_\odot$
- $D = 700$ kpc

NGC1569
- $Z = 1/4 \, Z_\odot$
- $D = 3.36$ Mpc

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SOFIA/FIFI-LS data: 30Dor

Chevance et al. 2020b

[Vista J]
[OIII] 88µm-FIFI-LS
[CII] 158µm FIFI LS
CO(3-2) ASTE

PACS [OI] 145µm coverage

FIFI-LS [OIII] and [CII] coverage
Spitzer, Herschel & SOFIA data: IC10

Polles et al. 2019
Polles et al. in prep.
SOFIA/FIFI-LS data: NGC 1569

*FIFI-LS [OIII] 52µm (smoothed)*

*PACS [OIII] 88µm*

Contours: [OIII] 52µm

Maps: C. Fisher
Empirical diagnostics:
Electron density in the ionised gas

$[\text{OIII}]$ 52µm / $[\text{OIII}]$ 88µm

NGC 1569

30 Dor

Chevance et al. 2020b
Empirical diagnostics: Electron density in the ionised gas

30Dor: electron density in the ionised gas $< 600$ cm$^{-3}$
Empirical diagnostics:

Electron density in the ionised gas

- 30Dor: electron density in the ionised gas < 600 cm\(^{-3}\)
- IC10: density ranges between 100 and 400 cm\(^{-3}\)
- NGC1569: electron density < 500 cm\(^{-3}\)
Empirical diagnostics: Hardness of the radiation field

Dwarf Galaxy Survey

\[ \rho = -0.36 \]

\[ \frac{\text{[OIII]}}{\text{[CII]}} \]

\[ 12 + \log(O/H) \]

Solar metallicity galaxies

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Empirical diagnostics: 
**Hardness of the radiation field**

Dwarf Galaxy Survey

$30\,\text{Dor}$

$\frac{[\text{CII}]_{158}}{[\text{OIII}]_{88}}$

$\rho = -0.36$

$12 + \log(O/H)$

Empirical diagnostics: Hardness of the radiation field
Empirical diagnostics: *Hardness of the radiation field*

- The ISM becomes more porous towards lower metallicities
Empirical diagnostics: 
*Hardness of the radiation field*

\[ ^{12}\text{CO} 2-1 \text{ (ALMA)} \text{ R. Indebetouw} \]
\[ \text{[NeIII]}, \text{[SIV]}: \text{Spitzer IRS (Indebetouw + 09)} \]
Modelling of the structure and physical conditions of the gas

The Meudon PDR code \citep{lepetit06,lebourlot14,bron14}

Model characteristics:
- Parallel slab geometry
- Gas phase abundances measured in 30Dor \citep{pellegrini11}
- Constant pressure

\[
G_{UV} \times 6.8 \times 10^{-14} \text{ erg cm}^{-3} \quad 1 \times 6.8 \times 10^{-14} \text{ erg cm}^{-3}
\]
(ISRF, local neighbourhood)

\[A_{V,\text{total}}\]
Modelling of the structure and physical conditions of the gas


Model characteristics:
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- Constant pressure

Key parameters:
- \(G_{UV}\): intensity of the *incident* radiation field
- \(P\): pressure of the cloud
- \(A_{v,\text{total}}\): visual extinction

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\(1 \times 6.8 \times 10^{-14} \text{ erg cm}^{-3}\)
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Constrained by [CII], [OI], $L_{\text{FIR}}$

Constrained by the ratios [CII]/[CII] or CO/[CII]
Modelling of the structure and physical conditions of the gas

30 Dor

contours: [CII]

Chevance et al. 2016
Chevance et al. 2020b
Emitted $G_{stars}$ from the cluster

Physical distance between stars and clouds: a 3D view of 30Dor

Physical distance to the center of the cluster

$$G_{stars} = G_{UV} \times \frac{L^2}{d^2}$$

Projected distance
Physical distance between stars and clouds: a 3D view of 30Dor

Chevance et al. 2016
Chevance et al. 2020b
Physical distance between stars and clouds: a 3D view of 30Dor

Chevance et al. 2016
Chevance et al. 2020b
What is the total reservoir of molecular gas?

Total H$_2$ mass predicted by the PDR model

Chevance et al. 2020b
What is the total reservoir of molecular gas?

Total $H_2$ mass predicted by the PDR model

\[ N(H_2) = X_{CO} \times I_{CO} \]

*Chevance et al. 2020b*
What is the total reservoir of molecular gas?

Total $H_2$ mass predicted by the PDR model

$N(H_2) = X_{CO} \times I_{CO}$

- More than 75% of the molecular gas not traced by CO

Chevance et al. 2020b
What is the total reservoir of molecular gas?

Total $H_2$ mass predicted by the PDR model

$$N(H_2) = X_{CO} \times I_{CO}$$

$$X_{CO}(30Dor) = \frac{N(H_2)}{I_{CO}}$$

Chevance et al. 2020b
Environmental variations of the CO-dark gas mass

The fraction of CO-dark gas is smaller closer to R136 (at high radiation field)
Environmental variations of the CO-dark gas mass

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- Due to the fact that clouds close to R136 (high radiation field) have higher $A_V$. 

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Environmental variations of the CO-dark gas mass

- The fraction of CO-dark gas is smaller closer to R136 (at high radiation field).
- Due to the fact that clouds close to R136 (high radiation field) have higher $A_V$.
- At higher $A_V$, the CO-free molecular envelope represents a smaller fraction of the total cloud mass.
Tracing the total molecular gas with [CII]

Madden et al. (2020)
Tracing the total molecular gas with [CII]

Model predictions show that:

- **[Cl]** and **[CII]** are good tracer of the molecular gas at low metallicity
- **[CII]** is a **better tracer** due to its higher luminosity

*Madden et al. (2020)*
Tracing the total molecular gas with [CII]

Model predictions show that:

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Madden et al. (2020) used a photoionisation model to determine systematically the CO-dark molecular gas mass from [CII] observations:

- \( M(H_2)_{\text{total}} = 10^{2.12} \times [L_{[C\ II]}]^{0.97} \)
- \( \alpha_{\text{CO}} = 10^{0.58} \times [Z/Z_\odot]^{-3.39} \)
Tracing the total molecular gas with [CII]

Star formation relation

Madden et al. (2020)

- Low-metallicity galaxies back on the standard star-formation relation
Tracing the total molecular gas with [CII]

Star formation relation

CO-to-H_2 conversion factor

- Low-metallicity galaxies back on the standard star-formation relation
- Steep slope of the CO-to-H_2 conversion factor with metallicity
How can we understand this slope?

- Based on the elemental abundances only, we expect CO abundance to scale \( \sim \) linearly with metallicity
How can we understand this slope?

- Based on the elemental abundances only, we expect CO abundance to scale ~ linearly with metallicity.

- The observed slope of $\alpha_{\text{CO}}$ with $Z$ is -3.39, much steeper than -1.

- How can we explain this?
How can we understand this slope?

- This can potentially be explained by an environmental dependent radiation field dissociating CO (H₂ self-shielded)
How can we understand this slope?

- This can potentially be explained by an environmental dependent radiation field dissociating CO ($\text{H}_2$ self-shielded)

- Can the UV photons emitted by young star-forming regions be responsible?
How can we understand this slope?

- This can potentially be explained by an environmental dependent radiation field dissociating CO ($\text{H}_2$ self-shielded)

- Can the UV photons emitted by young star-forming regions be responsible?

- How many photons escape during a star-forming region lifetime?
Evolutionary cycle between clouds, feedback phase and young stellar regions

- We have linked the spatial decorrelation between CO and Hα to their emission timescale.
  
  Kruijssen et al. (2018), Hygate et al. (2019), Haydon et al. (2020b)

Chevance et al. (2020a,c)
The observed “feedback timescale” exceeds the predicted timescale

if all emitted photons couple to the parent cloud

Chevance et al. (to be subm.)
The observed “feedback timescale” exceeds the predicted timescale

- Offset reflects the coupling efficiency between feedback and the surrounding ISM

if all emitted photons couple to the parent cloud
Coupling efficiency as a function of metallicity

Over the feedback phase

Over the stellar region lifetime

Chevance et al. (to be subm.)
Coupling efficiency as a function of metallicity

- Photoionisation as a source of feedback couples more efficiently with the ISM at high metallicity -> more photons escape at lower metallicity
Metallicity dependence of the CO-to-$\text{H}_2$ conversion factor

- The low CO/SFR and high [C II]/CO observed in low metallicity dwarf galaxies can be explained by the **photodissociation of CO**
  
  Madden et al. (2020)
Metallicity dependence of the CO-to-\( \text{H}_2 \) conversion factor

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- This is increased at low-metallicity due to a **more porous ISM**  
  Chevance et al. (in prep.)
Metallicity dependence of the CO-to-H$_2$ conversion factor

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- Results in the presence of a large reservoir of CO-dark molecular gas
Conclusions

- Using PDR modelling, FIR emission lines reveal the **3D structure** and the **physical properties** of the gas.
- In massive star forming regions the vast majority of the molecular gas is **CO-dark**.
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This is driven by:

- The **intense radiation field** from the central cluster

- The **high porosity** of the gas in moderate to low-metallicity environments, allowing a **large fraction of the photons to escape** young stellar regions and travel over tens of parsecs

- Next step: bridging cloud-scale conditions to the **larger scale environment**
**Future work**

**LMC+:** SOFIA Joint Legacy Proposal proposal with FIFI-LS (C9) on the LMC Molecular Ridge (*P.I.: S. Madden and A. Krabbe*)

- 50h: 1.3x0.5 deg map in [CII] and [OIII]
- physical conditions and thermal processes in the PDRs
- quantify the total molecular gas mass reservoir
- probe a wide variety of star-forming and ISM conditions
- complement the recent accepted ALMA proposal for CO observations of the ridge (*P.I.: Bolatto*)

**Simulated [CII] 158μm and [OIII] 88μm**

**MCELS Hα**

*Paredes et al. 2015*

**CO contours**

*MAGMA; Wong et al. 2011*
Conclusions

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