The ISM in low metallicity galaxies: The importance of CO-dark gas & phase structure

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Gas and Star Formation in Dwarfs

Kennicutt Schmidt; Kennicutt + 1998



⇒ Efficient SF from H₂?
 ⇒ (low) SF in atomic gas?
 ⇒ Time/evolution bias?

or CO not tracing the full H₂ mass?

 \Rightarrow What is the role & distribution of the different gas reservoirs in the SF process?

Metal-poor versus metal-rich galaxies

PDR diagnostic 10-2 -F.R ر الم 08 + Galactic SF Regions Starburst Nuclei Non-Starburst Nuclei △ Normal Galaxies O Local ULIRGs 10-4 + z>2.3 ¥z=1−2 SF HFLS3 (z=6.3) ¥z=1−2 mixed DGS Dwarfs LESSJ033229 (z=4.7) 10⁻⁸ 10⁻⁵ 10-7 Figure adapted from: 10-6 Madden 2000, 2019 L_{co(1-0)}/ Stacey et al. 2010 Hailey-Dunsheath et al. 2010

What is this telling us about the structure of the ISM?

Metal-poor versus metal-rich galaxies



Metal-poor versus metal-rich galaxies: ISM structure



CO-dark gas: *Roellig+2006; Wolfire+2010; Glover & Clark 2012* How much H₂ are we missing by using CO only ?

C+ on KAO: Local dwarfs (IC10, LMC, SMC, NGC6822): 10-100 times more CO-dark than CO-bright gas mass: *Poglitsch* +1995, *Madden*+1997, *Israel* +1997

Also via Gamma rays (Grenier+), dust,...

Modeling the Multiphase ISM of dwarfs:



Cormier et al 2019

 \Rightarrow Unresolved spatially & spectrally requires numerous model constraints for accurate description of galaxy phase structure & H₂ determination & physical processes

Modeling the Multiphase ISM of dwarfs:

Cormier et al. 2019: Cloudy models of the Dwarf Galaxy Survey

Multi-component model



Dense HII region: n=100 cm^{-3} , log U = -0.83, covering factor 60%

PDR: n=10000 cm⁻³, covering factor = 30%

Diffuse ionized component: n=10 cm⁻³, log U = -1.33, covering *factor* = 40%



Quantify the total H₂ & CO-dark gas: L_{[CIII/}CO, Av, L_{CO}



Madden et al. in prep.

Quantify the total H_2 & CO-dark gas: $L_{[CII]}$, CO, Av, L_{CO}



Madden et al. in prep.

open circles: upper limit in CO detections Red dots: CO detections

Retrieve the extreme [CII]/CO in dwarfs and higher [CII]/L_{FIR} (global scales).

ISM diagnostics: structure and physical conditions



ISM diagnostics: structure and physical conditions



Also: Polles et al. 2018 : resolved SF regions in IC10 => matter bounded

Structure and Metallicity Effects: covering factor of PDR



Metallicity (Z) decreasing

PDR Covering factor decreases

Quantify the total H₂ & CO-dark gas: [CII]/CO



Taking into account this dark reservoir of H₂ brings these galaxies on to the KS relationship or Bigiel 2008

Squares: H₂ from CO only (standard conversion) Circles: total H₂ from model

Take-away points: ISM of low metallicity environments

Low metallicity ISM

Filling factor of neutral PDR gas is low – scales with metallicity
Filling factor of ionized gas can be considerable

[OIII] (35 eV) is brightest FIR f.s. line, not [CII] (global scales!) *= the ISM is porous, allowing high energy photons to escape Can only get info on all phases with large variety of tracers*

Not tracing the bulk of the H₂ with CO observations only, in low Z environments.
 Vast majority of the molecular gas is CO-dark in low Z (even moderately low Z)
 => CO-dark gas favors low Av environments

More & extended analysis within nearby galaxies:

SOFIA & Herschel observations of more & varied regions in the LMC and SMC Antigone Lambert-Huyghe in prep - Cloudy modeling of Magellanic Clouds

JWST & ALMA will zoom into these structures in more detail

SPICA & OST will obtain rich diagnostic lines for most distant galaxies

Quantify the total H₂ & CO-dark gas: [CII]/CO



Squares: H₂ from CO only (standard conversion) Circles: total H₂ from model

Taking into account this dark reservoir of H₂ brings these galaxies nicely on the KS relationship or Bigiel 2008

Resolving low Z galaxies with SOFIA : H₂ Inventory LMC/30Dor



Resolving low Z galaxies: leaking HII regions: IC10



Polles et al. 2018 – see Fiorella Polles' Poster #40

15 MIR + FIR fine structure lines (Cloudy) Varied spatial scales: 25pc to 250 pc

From matter-bounded ISM on small scales to almost radiation-bounded ISM on large scales

Escape fraction from regions in IC10 $\sim 40\%$



Origin of [CII] How much [CII] can we expect in the [NII] emitting gas ?



Multi-phase models of (FIR)-unresolved objects



Haro₂

Model grid input parameters

Fixed:

Varied:

Initial density n_H Ionization parameter U (a posteriori) PDR covering factor

Resolving low Z galaxies: leaking HII regions: IC10



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Resolving low Z galaxies with SOFIA : H₂ Inventory LMC/30Dor



Resolving low Z galaxies with **SOFIA** : [OIII] line ratios & electron density: LMC/30Dor



Chevance et al. (in prep)

Resolving low Z galaxies with SOFIA: H₂ Inventory LMC/30Dor



Substantial (> 70%) molecular gas not traced by CO in Low Z Local Group galaxies: e.g.: SMC: Jameson et al 2018 (PACS – no vel. resolution [CII], [OI]) SMC : Requena-Torres et al. 2016 (SOFIA/GREAT vel resolution [CII] [NII]) LMC/N11: Lebouteiller et al. In prep (SOFIA/GREAT vel resolution [CII]) LMC & SMC: Pineda et al. 2017: (Herschel/HIFI vel resolution [CII], [CI]) NGC4214: Dimartos et al 2015 (SOFIA/GREAT vel resolution [CII])

Quantify the total H_2 & CO-dark gas: $L_{[CII]}$, CO, Av, L_{CO}

 $\begin{array}{ll} \mathsf{M}(\mathsf{H}_2)_{total} & \text{from model} \\ \mathsf{M}(\mathsf{H}_2)_{CO} & \text{from observations} \\ \mathsf{M}(\text{CO-dark gas}) = \mathsf{M}(\mathsf{H}_2)_{total} - \mathsf{M}(\mathsf{H}_2)_{CO} \end{array}$



Av decreases -> higher CO-dark gas fraction

L[CII] gives you the CO-dark gas mass

Taking into account this dark reservoir of H₂ brings these galaxies nicely on the KS relationship

Madden et al. in prep.