# CO-dark gas: What fuels the star formation in low metallicity dwarf galaxies?

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**Abstract.** While star-forming dwarf galaxies have little molecular gas traced by CO, their extreme observed [C II]/CO (1-0) and [O III]/[C II] ratios set them apart from metal-rich star-forming galaxies. The decreased dust abundance, along with their star formation activity, encourages the photodissociation of CO and the presence of relatively prominent $C^+$ envelopes which can harbor a significant self-shielded $H_2$ reservoir, with CO being an inaccurate proxy for the total $H_2$ gas mass. Modeling the Dwarf Galaxy Survey allows us to quantify the mass of the CO-dark $H_2$ gas and derive a [C II]-to-$H_2$ gas mass conversion factor as well as a new CO-to-$H_2$ conversion factor as a function of metallicity.

## 1 Introduction

As ALMA and JWST push back the frontier to reach early star-forming galaxies, metal-poor galaxies should become more prevalent. Studying the interstellar medium (ISM) of the vast diversity of low-metallicity dwarf galaxies in the local universe can lend some insight into the process of the conversion of gas into stars in metal-poor environments. Their striking observational signatures set they apart in several ways from their metal-rich counterparts.

While CO has been a long-time favorite proxy to quantify the mass of molecular gas in galaxies, numerous surveys of dwarf galaxies have found that CO is faint or non-detected in low metallicity dwarf galaxies [e.g. 1–3], leaving us with uncertainties in quantifying the total molecular gas reservoir in dwarf galaxies. These effects are dramatically demonstrated [e.g. 4] in the Kennicutt-Schmidt relationship which is often used as a recipe to relate molecular gas to star formation. Directly translating the total molecular gas reservoir via CO may lead to the conclusion that they are super efficient in forming stars. Or, are we accurately measuring the total molecular gas reservoir via CO in dwarf galaxies?

Another distinct observational characteristic in star-forming dwarf galaxies surrounds the [C II]$\lambda 158\mu$m line which is the most luminous emission line in the FIR to mm wavelength range in metal-rich star-forming galaxies on global scales [e.g. 5, 6]. $C^+$ is easily excited by 11.3 eV photons and dominates the cooling of the cool ISM, primarily arising from photodissociation regions (PDRs). In low metallicity star-forming galaxies, however, it is the FIR [O III]$\lambda 88\mu$m line, requiring ionisation energies of 35 eV, which dominates on global scales, not the [C II] line [7, 8], an effect now also observed in some high-z galaxies [e.g. 9, 10]. This reveals the ease at which such hard photons, originating from young O stars, can traverse full galaxy scales, with a very porous ISM structure in low metallicity galaxies. While

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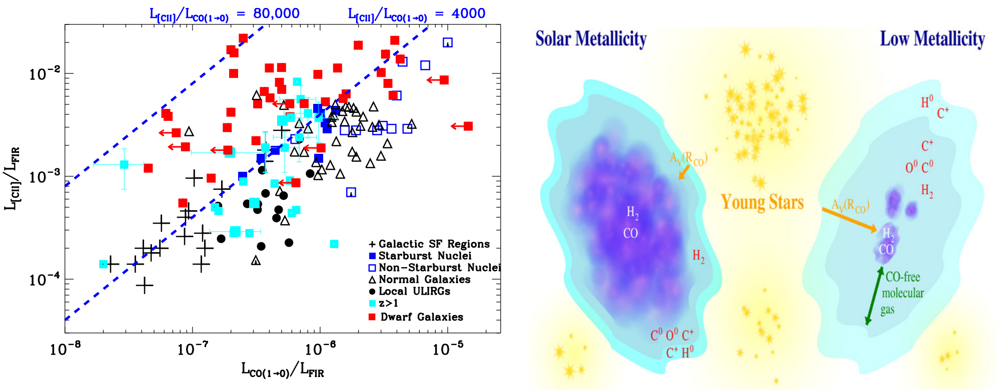


**Figure 1.** *left:* $L_{CO(1-0)}/L_{FIR}$ vs $L_{[C\,II]}/L_{FIR}$ observed in galaxies ranging widely in type, metallicity and in star formation properties. This is updated from [12, 14] to include dwarf galaxies [13]. The dashed lines show constant ratios of $L_{[C\,II]}/L_{CO(1-0)}$. Low metallicity dwarf galaxies (red squares) show extreme $L_{[C\,II]}/L_{CO(1-0)}$ values. *right:* Schematic comparing a metal-rich (solar) molecular cloud and a low-metallicity cloud impacted by UV photons of nearby star clusters. The decrease in dust shielding, in the case of the low metallicity cloud, leads to further photodissociation of molecular gas, leaving a layer of self-shielded $H_2$ outside of the small CO-emitting cores, associated with the $C^+$-emitting region. This CO-dark $H_2$ can be traced by [C II].

the observed $L_{[C\,II]}/L_{CO(1-0)}$ ratios in metal-rich disk and starburst galaxies have been shown from many surveys to range from ∼1000 to 4000 [e.g. 11, 12], $L_{[C\,II]}/L_{CO(1-0)}$ is observed on global galaxy scales in dwarf galaxies to stand out at much higher levels [13, and references within] (Fig. 1). These are some observational signatures which are effects of the decreased dust abundance and active star formation in the metal-poor dwarf galaxies which result in low average ambient radiation fields over the large galaxy scales, high ionization parameters and low covering factor of PDR gas. Consequently, the CO clouds suffer photodissociation surrounded by large [C II] envelopes.

## 2 CO-dark gas

Such extreme observational distinctions observed in low metallicity galaxies may be indicative of the presence of a reservoir of molecular gas that is not traced by CO, but residing in the $C^+$-emitting region. As $A_V$ is reduced, photons photodissociate CO, while the $H_2$, which photodissociates via Lyman-Werner band photons, can become optically thick and self-shielded from photodissociation (Fig. 1). This CO-dark molecular gas reservoir [e.g. 15, 16] can be traced by [C II] [13, and references within] under low $A_V$ conditions, leaving CO a poor tracer of the total $H_2$ at low metallicities. We describe our modeling strategy to quantify the total mass of $H_2$ in the low metalliciy galaxies of the Dwarf Galaxy Survey [DGS; 17].

## 3 Modeling Strategy

The DGS observed a wide range of local universe (0.7 to 190 Mpc), low-metallicity star-forming galaxies of the in MIR and FIR fine structure lines with *Herschel* and *Spitzer* providing ideal constraints for multi-phase Cloudy modeling. While many of the compact local dwarf galaxies are unresolved at these wavelengths, we can uncover properties of different galactic phases by exploiting the many fine structure lines of widely varying critical densities

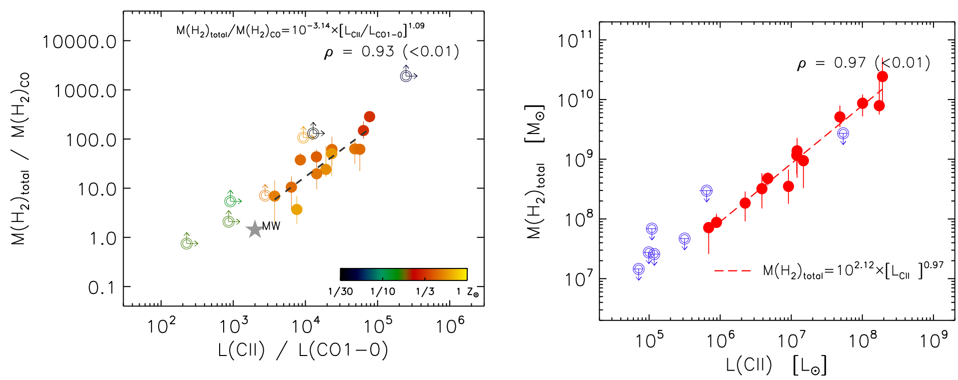


**Figure 2.** *left:* $M(H_2)_{total}$ / $M(H_2)_{CO}$ (total $M_{H_2}$ determined from the model over the $M_{H_2}$ determined from CO observations for the DGS, using the Galactic conversion factor) vs. observed $L_{[C\,II]}/L_{CO(1-0)}$ with color code for metallicity. *right:* $M(H_2)_{total}$ vs. observed [C II]. The open circles indicate limits in y-axis values due to upper limits in CO. The resulting fits for these relationships (dashed lines) are described in the panels with Spearman correlation coefficients ($\rho$) and p-values in parentheses [13].

and ionisation stages. The $L_{[C\,II]}/L_{CO(1-0)}$ relates to the depth of the molecular cloud and the $L_{[C\,II]}/L_{TIR}$ and $L_{[C\,II]}/L_{[O\,I]}$ ratios constrain the radiation field and density at the illuminated face of the PDR. The strategy is that once a well constrained Cloudy solution is reached, the self-consistent total molecular hydrogen mass from the model for each galaxy is extracted. The difference between the model solution for $H_2$ mass and the $H_2$ mass determined directly from the observed CO quantifies the mass of CO-dark gas. Application of the models to the wide range of environments of the DGS, using the observed [C II] and CO (1-0) observations (references in [13]), allows us to extract the total $H_2$ mass and determine the fraction of the total $H_2$ reservoir that is not traced by CO observations, investigating the role of galactic parameters (star formation rate, metallicity, $A_V$, etc) in the mass fraction of CO-dark gas. We find a fraction of CO-dark gas, $M(H_2)_{total}$ / $M(H_2)_{CO}$ based on $L_{[C\,II]}/L_{CO(1-0)}$ (Eq. 1) and a $L_{[C\,II]}$-to-$M(H_2)_{total}$ conversion factor (Eq. 2; Fig. 2). Acconting for the total mass of $H_2$ which includes the CO-dark gas mass, we find a new CO-to-$H_2$ conversion factor as a function of metallicity, which is steeper than previous conversion factors in the literature: $\alpha_{CO} = 10^{0.58} \times [Z/Z_\odot]^{-3.39}$ [13].

$$M(H_2)_{\rm total}/M(H_2)_{\rm CO} = 10^{-3.14} \times [L_{[\rm C\,II]}/L_{\rm CO(1-0)}]^{1.09} \tag{1}$$

$$M(H_2)_{\rm total} = 10^{2.12} \times [L_{[\rm C\,II]}]^{0.97} \tag{2}$$

## 4 Conclusion

We are studying local universe low metallicity environments to be able to relate their observational signatures to physical ISM properties and eventually lend insight into low metallicity early galaxies of the very high-z universe. We are able to carry out the detailed multi-phase modelling for local universe galaxies, where there is access to many observational spectroscopic tracers of different phases, which is not always the case for the high-z galaxies. From the global modeling of the Dwarf Galaxy Survey, we find that the combination of star formation and low dust abundance has a profound effect on the observational tracers, compared to their dustier counterparts. The ISM structure at low metallicity is very porous and clumpy with small filling factors of PDRs and high filling factors of ionized gas. Star forming dwarf galaxies stand out in their faint CO emission and uniquely high [C II]/CO (1-0) and [O III]/[C II] ratios. In some cases, up to ~ 90% of the total $H_2$ mass is missed when accounting for $H_2$ associated with the observed CO only. The bulk of the molecular gas, much of it CO-dark, can be traced by [C II]. Our modeling brings a new [C II]-to-$H_2$ mass conversion factor and a new CO-to-$H_2$ mass conversion factor. Taking into account this significant CO-dark $H_2$ reservoir, the star-forming dwarf galaxies shift to the Kennicutt-Schmidt relation found for dustier, star-forming disk galaxies. While our modeling has been applied to low metallicity galaxies, another step is to see if this can be applied in more general terms to galaxies.

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