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Bright ^{12}CO emission traces both dense and diffuse gas

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Abstract. We show that the $X_{\rm CO}$ factor, which converts the CO luminosity into the column density of molecular hydrogen has similar values for dense, fully molecular gas and for diffuse, partially molecular gas. We discuss the reasons of this coincidence and the consequences for the understanding of the interstellar medium.

Key words. Interstellar medium: molecules

1. Introduction

^{12}CO (J=1–0) emission is the main tracer of the molecular gas in our Galaxy as well as in external galaxies (see *e.g.* Leroy et al., 2008; Bigiel et al., 2008). Yet, this CO emission is ambiguous. Indeed, this CO emission is usually associated to cold (10-20 K), dense ($> 10^5\,{\rm cm^{-3}}$), strongly UV-shielded, molecular gas (*i.e.* carbon atoms are mostly locked in CO). However, it became more and more obvious over the last decade (Liszt & Lucas, 1998; Goldsmith et al., 2008) that a large fraction of the CO emission in our Galaxy comes from warm (50-100 K), low density (100-500 $\rm cm^{-3}$), weakly UV-shielded, diffuse gas (*i.e.* carbon atoms are mostly locked in C^+). Moreover, at the beginning of the history of the $X_{\rm CO}$ factor, Liszt (1982); Young & Scoville (1982) noted that diffuse and dense gas have similar factor. For instance, $W_{\rm CO} \approx 1.5\,{\rm K\,km\,s^{-1}}$, $N_{H_2} = 5 \times 10^{20}\,{\rm km\,s^{-1}}$ toward ζOph, a prototypical diffuse line of sight, and $W_{\rm CO} = 450\,{\rm K\,km\,s^{-1}}$, $N_{H_2} = 2 \times 10^{23} H_2$ toward Ori A, a prototypical dense gas line of sight. This triggers the question of the mean value of the $X_{\rm CO}$ factor in diffuse gas (Liszt et al., 2010, for details see).

2. How to measure the mean $N_{H_2}/W_{\rm CO}$ conversion factor in diffuse gas?

We quantify the $X_{\rm CO}$ conversion factor in diffuse gas from a sample acquired over the last 20 years. It is made from the study of whole Galactic lines of sight measured in absorption against extragalactic continuum background sources. There are two different groups of lines: Either they have a low visual extinction ($A_{\rm V} \lesssim 1$) when they are observed at high galactic latitude ($|b| \gtrsim 15-20$ deg) or when they lie in the Galactic plane, their large total visual extinction ($A_{\rm V} \sim 5$) can be divided in well separated velocity components, each one having $A_{\rm V} \lesssim 1$ mag (see the left column

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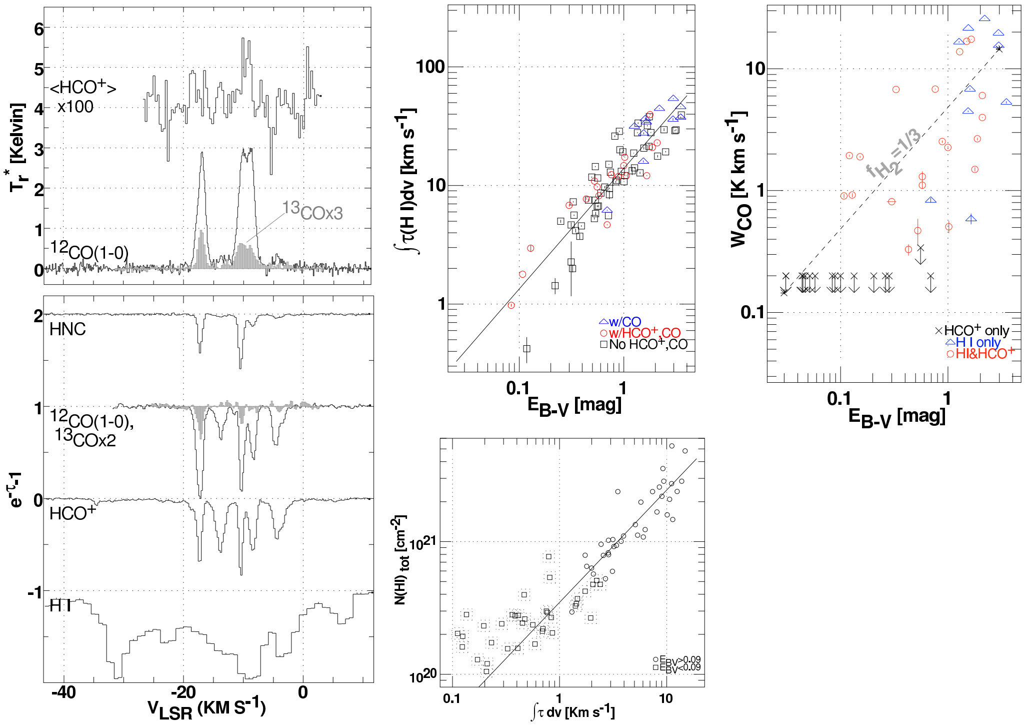

Fig. 1. Left: Example of the measurements available in emission (top) and in absorption (bottom) for one of the Galactic line of sights used in this study (for details see Pety et al., 2008). **Middle, top:** Integrated VLA HI optical depth from Garwood & Dickey (1989) and this work versus the total line of sight reddening from Schlegel et al. (1998). **Middle, bottom:** Total hydrogen column density versus integrated HI optical depth for the sources studied by Heiles & Troland (2003). **Right:** CO luminosity versus the total line of sight reddening from Schlegel et al. (1998).

of Fig. 1 for an example). Hence, all the gas studied here is diffuse. Indeed, the CO column density per velocity component on any line of sight is low, typically $N_{CO} \le 2 \times 10^{16}\,cm^{-3}$, which implies that less than 7% of the carbon is locked in CO.

The computation is then made in three steps. First, the total hydrogen column density is deduced from the E_{B-V} reddening maps of Schlegel et al. (1998), using the standard relation (Bohlin et al., 1978; Rachford et al., 2009)

$$N_H = N_{HI} + 2N_{H_2} = 5.8 \times 10^{21}\,H\,cm^{-2} E_{B-V}. \quad (1)$$

Second, we estimate the atomic gas fraction via the HI absorption measurements by writing it as the product of two terms

$$\langle f_{HI} \rangle = \left\langle \frac{N_{HI}}{N_H} \right\rangle \sim \left\langle \frac{N_{HI}}{\int \tau_{HI}\,dv} \right\rangle \times \left\langle \frac{\int \tau_{HI}\,dv}{N_H} \right\rangle, \quad (2)$$

where the left term is directly measured from the data (middle, top panel of Fig. 1) while the right term is calibrated from the careful measurements of Heiles & Troland (2003) (middle, bottom panel of Fig. 1). This gives $\langle f_{HI} \rangle = 0.65$ or $\langle f_{H_2} \rangle = 2N_{H_2}/N_H = 0.35$[1]. The third step consists in the measures of the CO emission luminosity, W_{CO}, along the line

[1] Others measured in diffuse gas gives $0.25 \le f_{H_2} \le 0.45$, which implies a 30% overall uncertainty on the method.

of sight (right panel of Fig. 1). We note here that the high W_{CO} values (> 10 K) arise from the accumulation of several low-A_V components along the same Galactic line of sight. Moreover, CO is not reliably detected at low E_{B-V} (< 0.3 mag). The corresponding lines of sight are not used in our estimation because the X_{CO} factor is used to estimate the molecular column density only from the CO gas which is detected. The dark gas infered both by Fermi (Abdo & Fermi/LAT Collaboration, 2010) and Planck (Planck Collaboration, 2011) could be, at least in part, accounted by the diffuse gas in these lines of sight. In summary, we obtain $\langle E_{B-V}\rangle = 0.89$ mag , $\langle f_{H_2}\rangle = 0.35$ and $\langle W_{CO}\rangle = 4.4\,\mathrm{K\,km\,s^{-1}}$, which give $N_{H_2}/W_{CO} = 2.04 \times 10^{20} \mathrm{H_2\,cm^{-2}/(K\,km\,s^{-1})}$, *i.e.* the same *mean* CO luminosity per H_2 in diffuse and dense gas!

3. Why a common N_{H_2}/W_{CO} conversion factor for diffuse and dense gas?

To understand this result, we write

$$\frac{N_{H_2}}{W_{CO}} = \left(\frac{N_{H_2}}{N_{CO}}\right)\left(\frac{N_{CO}}{W_{CO}}\right), \quad (3)$$

where the N_{H_2}/N_{CO} ratio comes from the CO chemistry while the N_{CO}/W_{CO} comes from the radiative transfer through the cloud structure.

In diffuse gas, more than 90% of the carbon is locked in C^+, which implies that $\langle N_{CO}/N_{H_2}\rangle = 3 \times 10^{-6}$ (Burgh et al., 2007). In addition, the gas is subthermally excited. Large velocity gradient radiative transfer methods (Goldreich & Kwan, 1974) thus show that 1) W_{CO}/N_{CO} is large because of weak CO excitation in warm gas (60-100 K), and 2) $W_{CO} \propto N_{CO}$ until the opacity is so large that the transition approaches thermalization. We thus obtain $N_{CO}/W_{CO} \simeq 10^{15} \mathrm{CO\,cm^{-2}/(K\,km\,s^{-1})}$ (see also Liszt, 2007).

In dense gas, all the carbon is locked in CO, *i.e.* $\langle N_{CO}/N_{H_2}\rangle = 10^{-4}$. As a consequence, N_{H_2}/W_{CO} = cst and $W_{CO} \propto N_{CO}$. A constant X_{CO} factor thus implies that $W_{CO} \propto N_{CO}$. We interpret this as a bulk effect in a turbulent medium, *i.e.* the medium is macroscopically optically thin because of the large velocity gradients due to turbulence.

The simulations of the CO emission from the interstellar medium by Shetty et al. (2011) are correct for the dense gas. However, a detailed comparison with our results on the diffuse gas shows that the radiative transfer factor is correct but there are up to 4 orders of magnitude difference in N_{H_2}/N_{CO}. This is linked to the poorly-understood polyatomic chemistry in the diffuse gas (see Shetty et al., 2011, their section 4.3).

In summary, the change of chemistry from diffuse to dense gas is compensated by the inverse change of the radiative transfer, giving the same X_{CO} factor.

4. How to discriminate diffuse from dense gas?

As ^{12}CO alone can not be used to discriminate between diffuse and dense gas, other tracers as molecules with higher dipole moments (*e.g.* HCO^+, CS, HCN) are tried. However, they often are difficult to detect. We thus propose to use the CO isotopologues, *i.e.* the ratio of the ^{12}CO over the ^{13}CO emission. Indeed, $T_{^{12}CO}/T_{^{13}CO} \gtrsim 10 - 15$ in diffuse, warm gas because of the C^+ fractionation (*e.g.* Liszt & Lucas, 1998), while $T_{^{12}CO}/T_{^{13}CO} \lesssim 3 - 5$ in dense, cold gas (*e.g.* Burton & Gordon, 1978).

5. What is the proportion of CO emission arising from diffuse gas in our Galaxy?

We here aim at estimating the CO luminosity of the diffuse molecular gas perpendicular to the Galactic plane from our absorption data for which the mean luminosity is $\langle W_{CO}\rangle = 4.6\,\mathrm{K\,km\,s^{-1}}$. We assume that the gas is simply ordered in plane-parallel, stratified layers. The Mean number of galactic half-width along integration path is then $\langle 1/\sin|b|\rangle = 19.8$, where b is the latitude of each line of sight of our sample. We thus obtain $\langle W_{CO_\perp}\rangle = 2\,\langle W_{CO}(b)\rangle\,/\,\langle 1/\sin|b|\rangle = 0.47\,\mathrm{K\,km\,s^{-1}}$.

The CO emission Galactic survey of Burton & Gordon (1978) gives a mean CO brightness per kpc of $5\,\mathrm{K\,km\,s^{-1}/kpc}$

at $R_{\odot} = 8$ kpc. Assuming a single Gaussian vertical distribution of dispersion 60 pc, we obtain $\langle W_{CO_{\perp}} \rangle = 0.75$ K km s^{-1}. This is a lower limit because we see large amount of CO emission outside area mapped by the Galactic surveys of the CO emission (mainly limited to the Galactic plane). Hence, a large fraction of the CO luminosity measured in Galactic surveys could come from diffuse gas.

6. Conclusion: Interpreting a sky occupied by CO emission from diffuse gas

The coincidence between the values of the X_{CO} factor in diffuse and dense gas implies that the mass estimates computed with the standard value are correct. However, the underlying physical interpretation of the detected gas is very different. If the gas is dense: it will fill a small fraction of the interstellar volume; it will be confined by ram or turbulent pressure (if not gravitationally bound); and it is on the verge of forming stars. If the gas is diffuse: it is a warmer, low pressure medium filling a large fraction of the interstellar volume; it contributes more the mid-IR or PAH emission; and it is probably not gravitionally bound or about to form stars.

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