Can We Trust CO as a Probe of the Densities and Temperatures of Molecular Clouds?

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Abstract We select a chemical magnetohydrodynamic simulation of molecular cloud formation and evolution as a typical example of a Galactic molecular cloud. Its analysis helps us understand how to interpret temperatures and densities inferred from CO line emission maps. We find that the kinetic temperature is always underestimated if it is inferred only from the excitation temperature, T_{ex}, of the ^{12}CO(1–0) emission line. We find also that CO primarily traces material at densities above the mean cloud density. In addition, we show that if one assumes a fixed value for the CO–H_2 conversion factor, then one will underestimate the density (and hence the mass) of H_2 at low column densities. In this scenario, the total H_2 mass of the cloud inferred from the emission map is only 60 % of the true mass.

Our simulation considers magnetized turbulent gas in a periodic box, and follows the chemical, thermal and dynamical evolution [1, 2]. It is characterized by a mean number density of $100\,cm^{-3}$, solar metallicity, volume $(20\,pc)^3$, and a turbulent RMS velocity of 5 km/s. We present results after three turbulent crossing times, when the turbulence has reached a statistical steady state. We use the Monte Carlo

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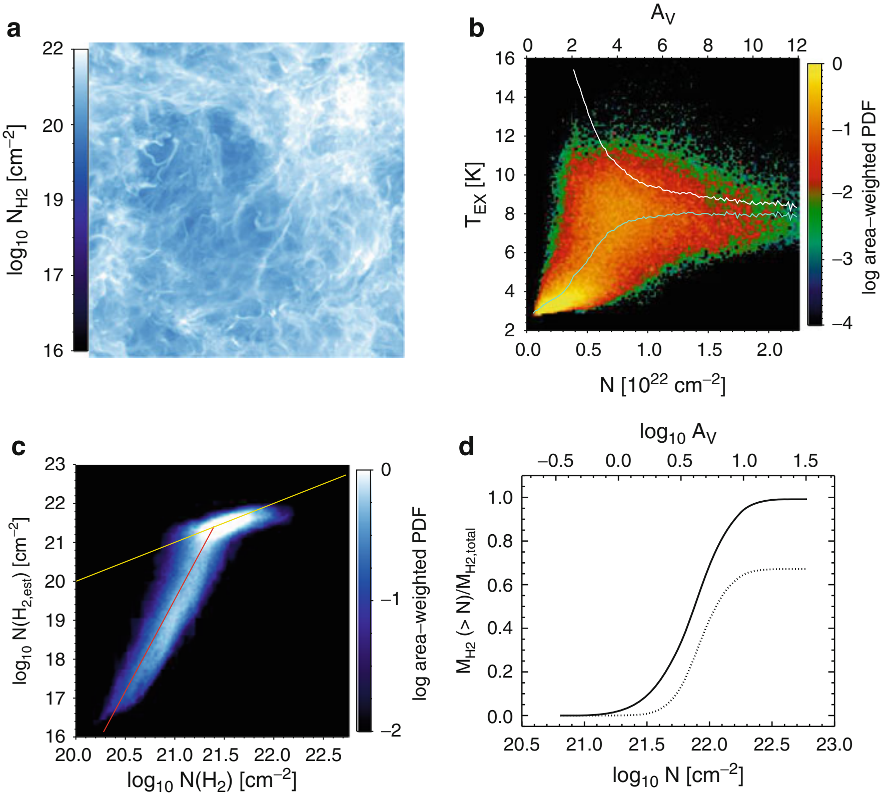

Fig. 1 (**a**) True H_2 column density. (**b**) 2D PDF of the projected T_{ex} vs. N, with reference to A_V. *Cyan line*: average of the T_{ex}, *white line*: CO mass weighted average along the LoS of T_K. (**c**) 2D PDF of the H_2 column density estimated from W_{CO} vs. the true H_2 column density. *Yellow line*: one-to-one relation. *Red line*: best fit to the low density gas. (**d**) Cumulative mass of H_2 – normalized by the total mass of H_2. *Dotted line*: inferred from W_{CO}. *Solid line*: true H_2 mass fraction

radiative transfer code RADMC-3D[1] to calculate the emergent CO line intensity [3]. Our aim here is to quantify the range of temperatures and densities where CO could be a good tracer of the physical conditions of the cloud.

Figure 1b shows the 2D Probability Density Function (PDF) of the excitation temperature (T_{ex}) calculated from the $^{12}CO(1–0)$ population levels. We see that the excitation temperature increases with increasing column density. On the other hand, the mean kinetic temperature at the CO ($\langle T_K \rangle$) starts with a high value but then decreases with increasing column density. The two values approach each other only at high column densities, $N \gtrsim 10^{22}\,\mathrm{cm}^{-2}$.

[1] http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/

In Fig. 1c, we show the 2D PDF of the H_2 column density ($N_{H2,est}$), estimated from the integrated emission map (W_{CO}), with a fixed CO–H_2 conversion factor $X_{CO} = 2 \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s, and the true N_{H2} (Fig. 1a). The values agree only at high densities, where the gas is optically thick. At low densities, the relationship lies far from the one-to-one relation. The cumulative mass of H_2 – normalized by the total mass of H_2 – as a function of N is shown in Fig. 1d. We compare the mass estimated from the emission map with true mass. The H_2 mass derived from W_{CO} is an underestimate at all densities. In total, the H_2 mass estimated from the W_{CO} map, and considering a fixed CO–H_2 conversion factor is only $\sim$60 % of the true value.

These results suggest that CO observations alone give a misleading view of the physical properties of molecular clouds. Complementary observations of the lower density gas using tracers such as C or C^+, are required.

References

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