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*Multi-line Diagnostics of the Interstellar Medium*

# Multi-line characterization of whole molecular clouds using stratified random sampling

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**Abstract.** We have developed a new technique to characterize the multi-line emission from molecular clouds using statistical sampling. Our method uses available extinction maps to select a relatively small sample of cloud positions that cover the full range of column densities in the cloud, and that can be observed with only a modest investment of telescope time. Here we present the first results of applying this technique to the Perseus molecular cloud, a nearby star-forming region that contains a population of both isolated and clustered protostars. We have used the IRAM 30m telescope to observe a sample of 100 random positions that cover two orders of magnitude in $H_2$ column density. These positions have been observed over the full 3mm wavelength band together with selected portions of the 2 and 1mm bands. We find that the emission properties of most species are strongly correlated with the column density over the whole cloud, and that they can be reproduced using a relative simple radiative transfer model.

## 1 Introduction

Characterizing the molecular emission from whole molecular clouds is critical to identifying the physical and chemical processes that act at different spatial scales and lead to the formation of stars. It is also needed to connect spatially-resolved observations of galactic clouds with extragalactic observations that do not resolve the clouds.

The traditional approach to characterize the emission of a cloud is to fully map its area with a telescope. Even when using a time-efficient technique such as on-the-fly mapping, this approach is very time consuming since it requires to fully sample the emission over many square degrees in the sky. Until recently, the mapping of clouds has only been carried out using a very reduced number of tracers (mostly CO), and for selected molecular clouds ([3, 7]). Thanks to the advent of the wide-band receivers, recent years have seen a renewed effort to characterize the emission of molecular clouds using multiple tracers. Examples of this effort are the two IRAM Large Programs ORION-B and LEGO, which have used the IRAM 30m telescope to map large extensions of several target clouds ([1, 6], and related contributions in this volume). Still, the time required to carry out these maps typically exceeds several hundreds of hours, and this strongly limits the ability to extend this approach to multiple clouds.

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While mapping a cloud is necessary to fully characterize its detailed emission and complex velocity field, such an effort likely provides more information than is necessary to determine the main cloud emission properties. Molecular clouds are turbulent objects, and much of their appearance is likely highly transient. For this reason, it is tempting to try to characterize the emission of a cloud using a less time-intensive technique, such as random sampling, which could potentially recover the main properties of the emission at a significant fraction of telescope observing time. In this contribution we present our attempt to use this technique to characterize the emission of the nearby Perseus cloud with the IRAM 30m telescope. A full account of this work has been presented in [8].

## 2 Method and observations

Our sampling method uses the $H_2$ column density as a proxy for the molecular emission since principal component analysis has shown that $N(H_2)$ represents the dominant contributor to the emission of most species (e.g., [4]). Sampling the cloud emission therefore requires to first sample its distribution of $H_2$ column densities, and for this, we have used the high quality column density map of Perseus produced by [9] with data from the *Herschel* and *Planck* satellites. This map extends over an area of more than $30 \times 10$ pc$^2$, and covers approximately two orders of magnitude in column density ($10^{21}$-$10^{23}$ cm$^{-2}$). To cover this wide range of column densities, we divided it into 10 logarithmically-spaced bins of 0.2 dex width and chose 10 random cloud positions inside each bin. This approach represents an instance of the so-called *stratified random sampling*, which is often used in polling. Our choice of 10 positions per bin is a compromise between observing enough positions to derive statistically meaningful parameters and accumulating enough integration time per position to detect the emission from the lowest column density bin.

The selected 100 cloud positions were observed with the IRAM 30m telescope using the EMIR receiver followed by the FTS spectrometer configured to provide a velocity resolution of 200 kHz ($\approx$ 0.6 km s$^{-1}$). The observations covered the full available 3mm wavelength band (83.7-115.8 GHz) together with selected portions of the 2 and 1mm bands to include additional transitions of the main 3mm tracers. All data were obtained in frequency switching mode, reduced with the GILDAS software, and converted to the main beam brightness temperature using the recommended telescope efficiencies.

## 3 Results

Fig. 1 summarizes the observational results of our Perseus emission survey and presents the intensity distributions of the different transitions as a function of $H_2$ column density. The top row shows the intensity distribution of the CO isotopologs, the middle row shows the distribution of so-called traditional dense gas tracers (but see, e.g.,[1, 6]), and the bottom row shows the distribution of additional tracers of dense gas. As can be seen, there is a significant correlation between the intensity of each line and $N(H_2)$, a result that supports our initial assumption that the $H_2$ column density represents a good proxy of the molecular line intensity. The typical dispersion of the intensities inside each column density bin is 0.2 dex for both the CO isotopologs and the traditional dense gas tracers, while the additional tracers present a slightly larger dispersion of about 0.3 dex.

An inspection of Fig. 1 reveals a variety of intensity distributions. The main CO isotopologs ($^{12}$CO and $^{13}$CO) present an abrupt drop toward the lowest column density bin, likely due to molecular photo-dissociation by the interstellar UV radiation field at the outer edge of the cloud . Toward the cloud interior, the $^{12}$CO and $^{13}$CO intensities present slopes

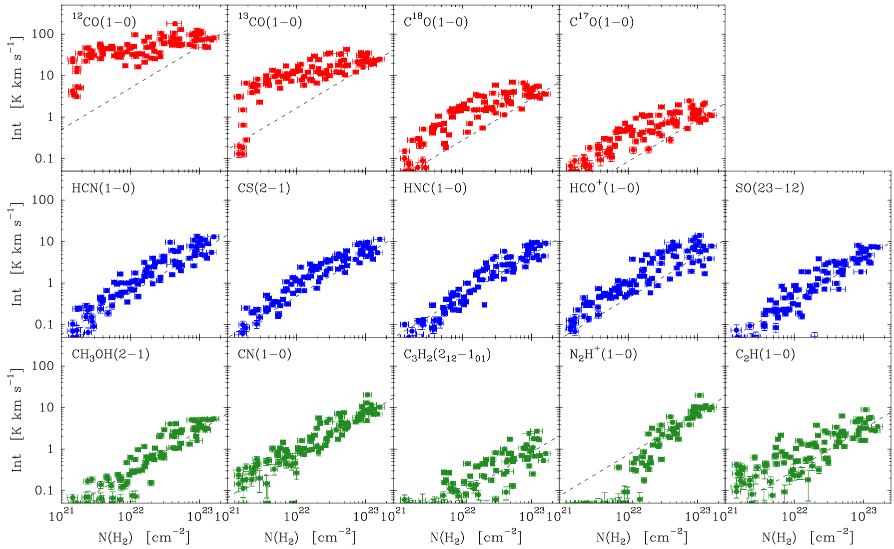


**Figure 1.** Distribution of integrated intensities of the main molecular species detected toward the Perseus cloud. The dashed lines show a linear trend for comparison.

that are significantly flatter than linear (dashed line), and effect that seems to be caused by the combination of thermalization and high optical depth (see below). The $C^{18}O$ and $C^{17}O$ lines are optically thinner, but they still present flatter-than-linear intensity distributions likely caused by freeze out at high column densities.

In contrast with the relatively flat distribution of the CO isotopologs, most dense gas tracers (Fig. 1 middle and bottom rows) present a close-to-linear distribution over the two orders of magnitude range of column densities. A slight flattening at high column densities can be seen in species such as HCN and CS, and is likely due to a combination of optical depth and freeze out. CN and $N_2H^+$, on the other hand, do not flatten out at the highest densities, indicating a stronger resistance to freeze out ([2, 5]). Among all the tracers, however, $N_2H^+$ is the only one that is truly selective of the densest gas component since its emission drops abruptly for $N(H_2)$ values lower than approximately $10^{22}$ cm$^{-2}$. This special behavior likely results from the strong sensitivity of its abundance to the presence of CO in the gas phase ([2]), and makes $N_2H^+$ the tracer of choice to identify the densest gas in a cloud.

The relative simplicity of the intensity distributions seen in Fig. 1 suggest that it may be possible to model the molecular emission of Perseus with a relatively simple model. For this, we have used a large velocity gradient (LVG) radiative transfer code and assumed that the cloud parameters only depend on the $H_2$ column density. Combining a constant temperature of 11 K, a volume density law that is proportional to $N(H_2)^{0.75}$, and abundance profiles for most species that contain both a photo-dissociation edge and freeze out at high column densities (with the obvious exception of $N_2H^+$), it is possible to reproduce the main trends observed in the data (see [8] for further details). The left panels of Fig. 2 illustrate the results of this modeling for the main and rare isotopologs of CO, CS, and HCN. As can be seen, the model fits both main and rare isotopologs of the three species assuming standard isotopic ratios and similar abundance profiles with molecular freeze out at high column densities. Although not shown in the figure, the model also fits the $N_2H^+$ emission assuming that this species survives at high densities and disappears when CO is present in the gas phase.

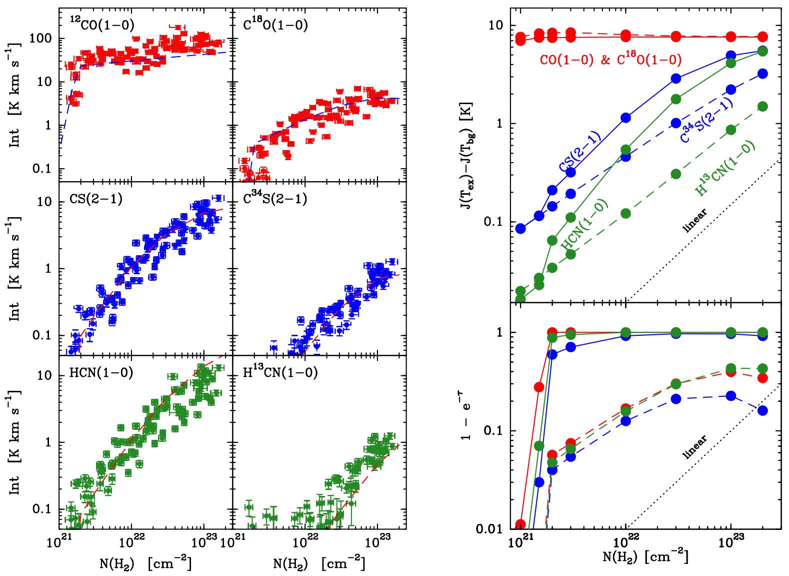


**Figure 2.** *Left:* Integrated intensity distributions of different isotopologs of CO, CS, and HCN together with the results of a simple radiative transfer model. *Right:* Excitation (top) and optical depth (bottom) terms of the equation of radiative transfer predicted by the cloud model. The main difference between the emission of CO and the dense gas tracers CS and HCN arises from their different excitations (top).

Given the success of our radiative transfer model in reproducing the observed intensities, we have used its results to explore how the emission is generated inside the cloud. The right panels of Fig. 2 represent the two terms of the radiative transfer solution, which we designate as the excitation term (top) and the optical depth term (bottom). As can be seen, the excitation of the CO isotopologs is very different from that of CS and HCN. While both CO isotopologs are thermalized through the cloud, the isotopologs of CS and HCN are strongly subthermal, and their excitation depends strongly on $N(\mathrm{H_2})$. The optical depth term (bottom panel), on the other hand, shows that all species follow similar patterns: the emission from the main isotopologs is optically thick, while the rare species are thin. Differences between CO and the dense gas tracers, and the quasi-linear dependence of their intensity, therefore results from the strong increase in the (subthermal) excitation toward the cloud interior.

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