Towards robust estimations of molecular cloud physical conditions from multi-species lines: The case of the Horsehead nebula

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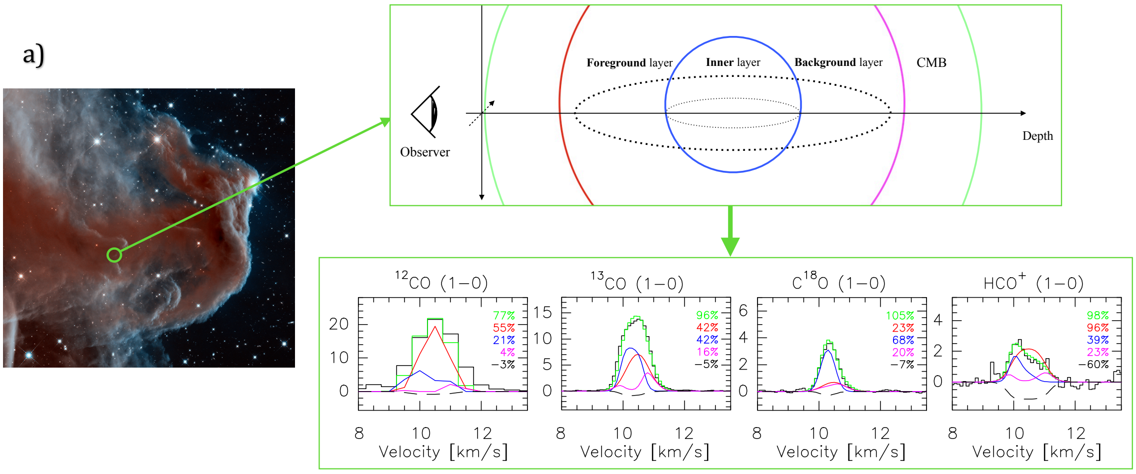
Performing robust estimations of kinetic temperatures (T_{kin}) and H_2 volume densities (n_{H_2}) for a substantial fraction of the volume of Giant Molecular Clouds is key to progress on our understanding of star formation in galaxies. This estimation relies on models of the excitation of molecular lines. However, important control variables of the radiative transfer equation, such as the geometry along a given line, are poorly known. It thus requires to inject a priori information on the gas physical and chemical properties (e.g., a simplified geometry and the relative abundances of the observed molecules).
The estimations can be strongly biased when these a priori are incorrectly set [1]. In particular, in the context of the analysis of the emission from multi-species, assuming homogeneous gas properties along lines of sight sampling a dense core and its envelope may lead to incorrect interpretations. Indeed, to overcome this issue, one should take into account that the different molecular tracers are sensitive to the different physical regimes encountered along the sight-line: cold dense gas in the core and warmer more diffuse gas in its envelope.

We therefore introduce a two-layer model to infer T_{kin} and n_{H_2} by fitting the spectra of the low-J transitions of the CO and HCO^+ isotopologues. The chosen field of view for testing the method is the region around the Horsehead nebula in the Orion B cloud. This region offers a diversity of environments (translucent gas, filaments, starless dense cores, and an edge-on photodissociation region). We fit the data with a maximum likelihood estimator including some constraints on the ratio of column densities. The proposed model allows us to simultaneously reconstruct the spectra of the selected molecular lines that probe different gas regimes while providing a simple description of the potential radiative coupling between the different layers along the sight-line. To check the relevance of the method, we also quantify the impact of the chemical knowledge, such as abundance ratios, on the maps of the estimated parameters and the associated reconstructed line fluxes. This study shows the benefit of having resolved spectra from multi-species data. It also paves the way for an analysis of the data of the ORION-B Large Program acquired at the IRAM-30m telescope, as well as future such datasets that will naturally be observed with the next generation of multi-beam receivers.

b)

a)



c)

Figure: **a)** The Horsehead nebula observed in the infrared light with the NASA's Hubble Space Telescope (NASA, ESA, and the Hubble Heritage Team (STScI/AURA)). The green circle indicated the line of sight at R.A, Dec. = 05h41m07.2s, −02◦27′19′′.
b) Sketch of the two-layer model of the sight-line: the inner layer is surrounded by an external layer, made of the foreground and background layers from the observer point of view. The CMB is the Cosmic Microwave Background. **c)** Spectra of the J=1-0 transition of ^{12}CO, ^{13}CO, $C^{18}O$ and HCO^+ (in plain black line) measured in this sight-line. The fit of the two-layer model (in green line) to measures is the sum of the spectra resulting from the foreground, inner, background layers and the CMB (in red, blue, pink and dashed black line respectively). Percentages indicate the contribution of the reconstructed flux of each layer to the measured one.

References

[1] Roueff et al., 2024.

[2] Segal et al., submitted to A&A.