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SYNTHETIC CO SPECTRA OF MOLECULAR CLOUDS

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Abstract. The origin and value of the peak of the stellar Initial Mass Function is a cornerstone of our understanding of the universal processes at work in the star formation sequence. The current paradigm, in which the characteristic stellar mass is inherited from the earliest stages of star formation, in molecular clouds, is a matter of debates. The comparison of observed hyperspectral datacubes of the carbon monoxyde emission from molecular clouds with synthetic observations based on (magneto-)hydrodynamical numerical simulations is a promising way to make progress. Such synthetic cubes are also most useful to benchmark analysis methods applied to observations. We present results from a simplified approach towards the generation of such synthetic observations.

Keywords: Molecular clouds, Star Formation, Initial Mass Function, Dense cores; numerical simulations, observations

1 Introduction

Stars form in molecular clouds as a result of competing and coupled processes driven by gravity in strongly supersonic turbulent flows. The distribution of newly formed stellar masses, the stellar Initial Mass Function (IMF), exhibits a peak indicating the existence of a characteristic mass, the origin of which remains to be fully understood (Bastian et al. 2010; Lee et al. 2020). It has been proposed that the IMF is determined at the earliest stages of star formation, the dense cores; indeed, the Dense Core Mass Function (DCMF) has a shape very close to that of the IMF, and shifted towards higher masses suggesting an efficiency of 30% from dense cores to stars. Yet, this paradigm is the matter of intense debates. Indeed, many questions remain about the nature, formation, and evolution of dense cores.

Large surveys of dense cores in molecular clouds have been performed with the Herschel satellite, using far-infrared thermal dust emission (André et al. 2010; Arzoumanian et al. 2019). Dense cores, identified through the column density contrast with their environment, are preferentially found in filaments, suggesting an evolutionary sequence beginning in turbulent molecular clouds, forming filaments which become gravitationally unstable thus forming dense cores, a subset of which would subsequently form stars. While this scenario provides a convenient framework, the formation of massive filaments remain elusive, while the identification of dense cores raises the question of how to isolate early condensations out of their environment. In parallel to large surveys, numerical simulations of strongly supersonic, turbulent molecular clouds follow the formation of dense structures towards gravitational collapse and the formation of stars (Federrath 2015). Further progress requires to bring both observational and numerical fronts onto a common footage for quantitative comparisons. Synthetic observations are also useful to benchmark analysis methods of turbulence. Producing synthetic hyperspectral CO datacubes is the aim of the present work.

2 Synthetic CO spectra

The modeling of CO spectra requires several steps: chemical calculations, radiative transfer, synthetic observations. The formation of CO from atomic carbon and oxygen involves an array of processes such as photoreactions and reactive collisions. Ideally, this needs to be followed with time in a self-consistent fashion with the dynamics and thermal evolution of the gas (Borchert et al. 2022). In the present work, we have developed a simple, but

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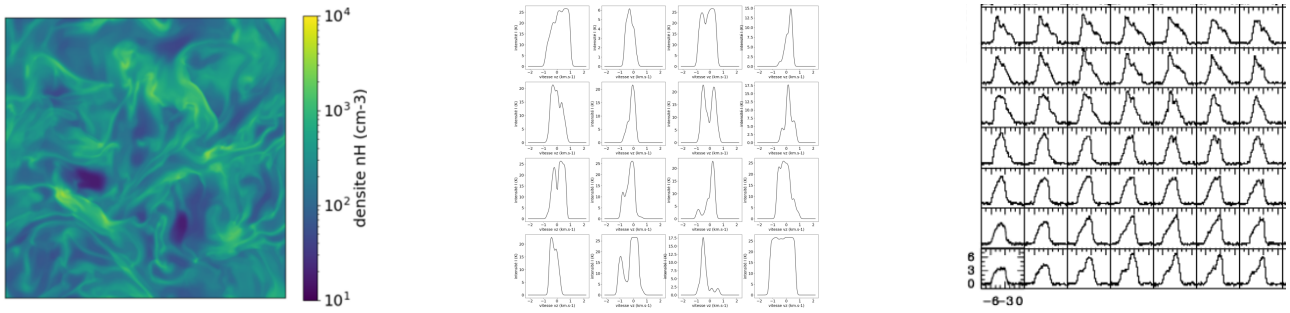

Fig. 1. Example of synthetic ^{12}CO(1-0) spectra based on the 256^3 simulations of Cho & Lazarian (2003) from the CATS database (Burkhart et al. 2020). The simulation was scaled adopting an average hydrogen density $n_{\rm H} = 300\,{\rm cm}^{-3}$, a kinetic temperature of 30K, and a total mass of $M = 30\,M_\odot$. Left: $n_{\rm H}$ density in a slice. Middle: modeled spectra; the intensity is typically 15-25K. Right: a random sample of spectra in the Polaris molecular cloud.

realistic, parametrization of the C^+/C/CO transition, using the total density, visual extinction, and kinetic temperature as parameters. This is based on detailed computations, which include all relevant chemical processes, under fixed and uniform physical conditions but covering a wide parameter space Gong et al. (2017). We also used results from the PDR Meudon code (Le Petit et al. 2006) for an isobaric slab, with varying density and temperature resulting from thermal balance. The visual extinction is calculated as the minimum of the total column density in the 6 directions for each cell. The radiative transfer is also highly simplified in this first approach. The rotational level populations are computed in LTE at the local temperature, based on the detailed calculations of Borchert et al. (2022). This allows us to compute a Gaussian opacity profile in each grid cell, using the local CO column density and velocity dispersion. To mitigate the classical divergence of explicit integration schemes in high opacity cells, we use the analytical solution of the radiative transfer equation for a uniform slab.

Figure 1 show a random sample of synthetic ^{12}CO(1-0) spectra obtained using the isothermal trans-Alfvénic and supersonic (sonic Mach number, $\mathfrak{M}_s$=2; Alfvénic Mach number, $\mathfrak{M}_a$=2) simulations of Cho & Lazarian (2003) and available from the CATS database (Burkhart et al. 2020). The dimensonless cubes of density and velocity were brought into physical units by adopting an average hydrogen density $n_{\rm H} = 300\,{\rm cm}^{-3}$, a kinetic temperature of 30K, and a total mass of $M = 30\,M_\odot$. Although the intensity is typically $15 - 25$K, thus significantly larger than a random sample of spectra in the Polaris molecular cloud, the line shapes show the typical diversity found in turbulent molecular clouds, from flat-top to multi-peaked spectra. Calculations performed with strongly supersonic simulations ($\mathfrak{M}_{\rm s}$=14.3) deviate from observed shapes, showing up to four peaks, and broad high-opacity plateaus.

3 Conclusions and perspectives

The work presented here is a first approach towards the generation of synthetic hypercubes of CO emission rotational spectra. Nevertheless, we obtain realistic spectral line shapes, although with too high an intensity compared to observed spectra. The impact of the physical parameters (density, temperature, mass) will be explored. In a second step, more realistic radiative transfer calculations, using the RADMC-3D code, will be performed.

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