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SMALL-SCALE DISSIPATIVE STRUCTURES OF THE DIFFUSE ISM: CO DIAGNOSTICS

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Abstract. Observations of translucent molecular gas in the emission of CO and ^{13}CO lines, with high spectral and spatial resolutions, evidence structures at small scales. The sensitivity of our observations allows to map the optically thin ^{12}CO and reveals that it is not uniformly distributed but forms warm filaments with high aspect ratio. The ^{12}CO and ^{13}CO(1-0) emissions consist of elongated structures whose orientations are parallel to the plane of the sky projection of the magnetic fields. From the statistical analysis of the velocity field, the ^{12}CO-thin filaments are found to coincide with the regions of largest velocity shear. Combining our data to large-scale observations with poorer spatial resolution, we show that these regions remain coherent over more than a parsec. These warm filaments are proposed to be the sites of the intermittent dissipation of turbulence.

1 Introduction

Star formation proceeds by condensating gas. While the steps from dense cores to hydrogen burning stars are basically identified, what triggers the building of these condensation seeds remains largely unknown.

Turbulence in the cold neutral medium is driven at large scale by the warm neutral flow. Dense cores thus form in a turbulent molecular gas with typical linewidth $3-4$ km s^{-1}. The role of magnetic fields during their formation is still a matter of strong debate (Crutcher 1999, Padoan et al. 2001). Observations of molecular lines show that the condensation proceeds at the expense of the turbulent support, as traced by the linewidth, and that some turbulent dissipation must take place in the molecular gas. Turbulence is dissipated at small scales. But how small is the dissipation scale ? Small-scale structures have been observed in the ionized and atomic gas down to few AUs, direct observations of molecular small scale structures are less common. Direct evidence of small-scale molecular structures include Pan et al. (2001) (10^4 AU with density 1000 to 5000 cm^{-3}) and Heithausen 2006 (few hundreds AU and densities $> 2\times10^5$ cm^{-3}). Indirect evidence of such small scale structures (200 AU) were indeed infered from translucent gas observations by Falgarone et al. (1998, F98).

Our work focusses on regions of low visual extinction ($A_V \leq 1$ mag) in the vicinity of dense core formation sites. Our large maps, with high spectral resolution ($\approx 5\times10^6$ or 0.055 km s^{-1} at 115 GHz), extend the dataset of F98 and allow to perform statistical analysis of the velocity field to relate the small-scale structures to turbulence.

2 Diffuse molecular gas structured at small scales

Figure 1 (top) shows maps of the integrated emissions of the ^{12}CO and ^{13}CO$(1-0)$ towards the Polaris Flare (F98, Hily-Blant & Falgarone 2006), done with the IRAM-30m telescope. The ^{13}CO emission is distributed along a main structure with a position angle P.A.$\approx$ 110 degrees. This structure is connected to a dense core, visible at the eastern edge of the map (Gerin et al. 1997). These maps show regions where only the ^{12}CO is detected. The channel maps and individual spectra show that these regions correspond to velocity intervals where the ^{12}CO over ^{13}CO$(1-0)$ line ratio is greater than 30. These intervals are called line-wings. The following work is devoted mainly to the physical properties, kinematics and dynamics of the emission in these wings.

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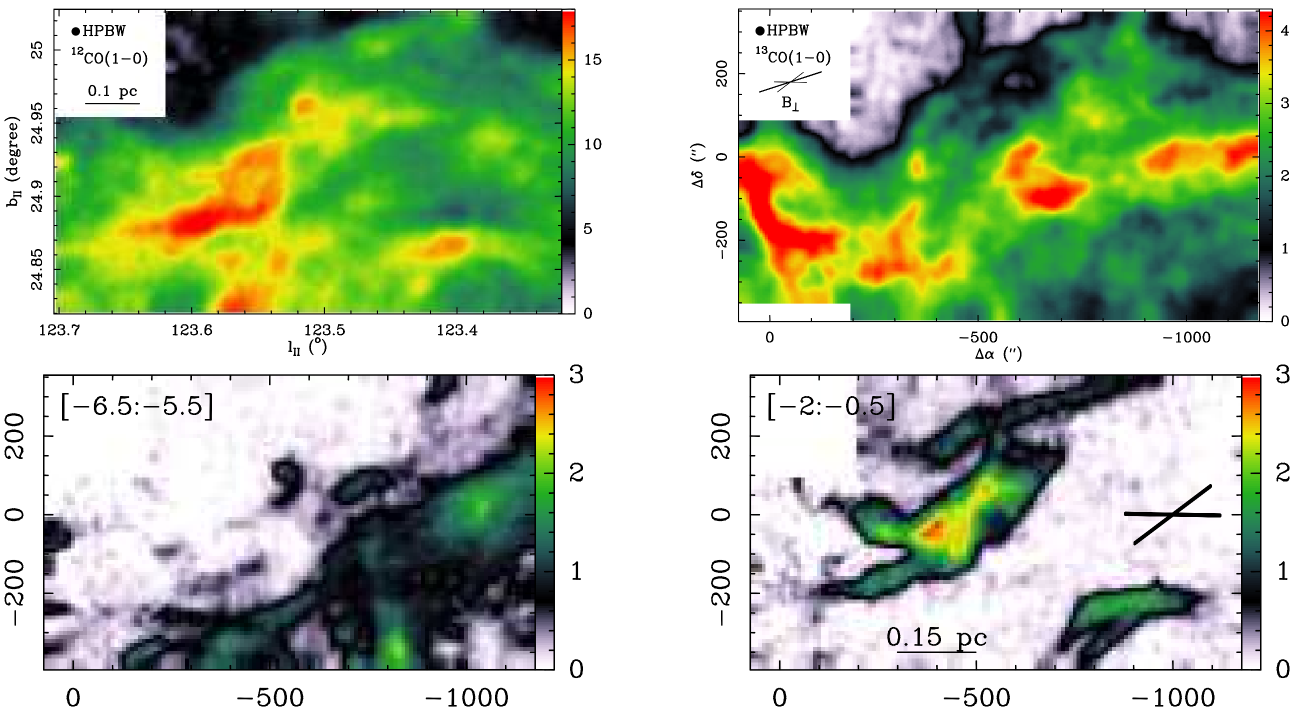

Fig. 1. *Top*: integrated emissions of the ^{12}CO (left) and ^{13}CO(1-0) (right) transitions. *Bottom*: ^{12}CO emission in the linewings intervals (see text): $[-6.5:-5.5]$ and $[-2:-0.5]$ km s^{-1}. The direction of the magnetic fields (with 1σ uncertainty) projected on the plane of the sky is indicated.

2.1 Small-scale optically thin ^{12}CO filaments

Figure 1 (bottom) shows the ^{12}CO(1-0) emission in the wing intervals ($[-6.5:-5.5]$ and $[-2:-0.5]$ km s^{-1}). Small elongated structures with typical transverse size 0.04 pc and velocity width 0.35 km s^{-1} are seen, and with aspect ratio as high as 10. Most of these are not detected in any channel in ^{13}CO. LVG analysis using ^{12}CO(1-0) and (2-1), combined with an upper limit on the H_2 column density provided by the visual extinction (Cambrésy 1999), shows that these filaments have kinetic temperatures greater than 20 K and densities smaller than 1000 cm^{-3}. They have a well defined column density $N_{\rm CO}/\Delta v = 3\times10^{15}{\rm cm}^{-2}({\rm km\ s}^{-1})^{-1}$ and ^{12}CO$(1-0)$ opacity ≈ 0.2. Compared to the material detected in ^{13}CO ($T_{\rm kin} = 8-9$ K and $n_{\rm H_2} \approx 1-2\times10^3{\rm cm}^{-3}$), these ^{12}CO-filaments are thus warmer and more tenuous.

2.2 Magnetic fields

The analysis of the structure in the ^{12}CO and ^{13}CO with automatic procedures (Stutzki & Güsten 1990) shows that the emission from both isotopologues arises in elongated filamentary structures, whose orientation is not random. The distribution of their position angles is peaked around P.A.$=105\pm40°$. Interestingly, the plane of the sky projection of the magnetic fields orientation, measured 4 pc North, has P.A.$=108\pm19°$ (Heiles 2000).

3 Dissipative structures of interstellar turbulence

3.1 Observable signature of intermittency

An attested deviation to Kolomogorov's 1941 turbulence theory is the fact that dissipation is intermittent, in space and time: the fraction of the volume and the timescale over which dissipation is active decreases with spatial scales. While the turbulent velocity can follow a Gaussian distribution, intermittency makes its increments over a distance l to depart from a Gaussian: tails show up because large increments are more numerous. This non-Gaussianity is more pronounced when decreasing l. As a consequence of intermittency, the

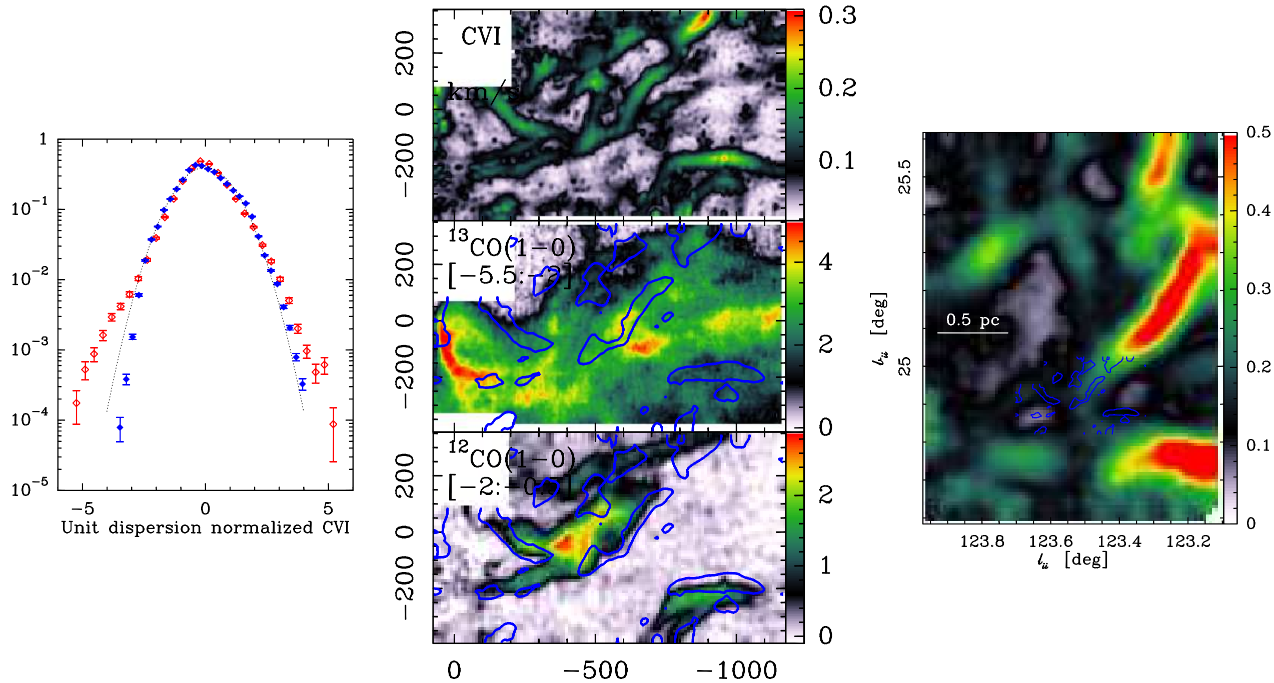

Fig. 2. *Left panel*: Probability density function (PDF) of the centroid velocity increments, normalized to unit dispersion (in blue, for a $l = 18$ pixels, in red $l = 3$ pixels). *Middle panel*: from top to bottom, *i)* spatial distribution of the centroid velocity increments in the ^{12}CO(1-0) emission (km s^{-1}), *ii)* integrated emission of the ^{13}CO(1-0), *iii)* ^{12}CO emission in the range $[-2 : -0.5]$ km s^{-1}. The 0.12 km s^{-1} CVI contours are indicated in blue. *Right panel*: CVI map calculated on the large-scale Kosma data (Bensch et al. 2001) with the contours from the middle panel.

velocity shear ($\partial_i v_j$) reaches large values at small scale and over short time scales, therefore producing bursts of viscous dissipation ($\propto \sigma^2 = \frac{1}{2}\sum_{ij}(\partial_i v_j + \partial_j v_i)^2$, with $\mathbf{v}$ the local fluid velocity). These violent events are associated to the non-Gaussian tails of the distribution of the velocity shear.

3.2 Intermittency in the interstellar molecular gas

Interstellar turbulence can only be partially probed: we measure the gas velocity projected along the line of sight (LOS) and the position projected in the plane of the sky (POS). All observables are LOS integrals: they result from a complex combination of radiative transfer in lines, chemistry, density and velocity structures of the gas. Lis et al. (1996) have shown that in the case of optically thin lines, the increments of line centroid velocities (CVIs) measured between two different LOS trace a quantity related to $\langle \omega_{POS} \rangle$, the LOS average of the POS projection of the vorticity. It is therefore possible, from the CVIs statistics computed in a map of spectra, to approach that of the vorticity and find the subset of space where the departures from a Gaussian distribution occur.

We have computed maps of CVIs for different lags, in the ^{12}CO(1-0) data, following Pety & Falgarone (2003). Fig. 2 (left) shows their probability density function for two lags $l = 18$ pixels (the largest lag with a significant number of pairs of points) and $l = 3$ pixels (the smallest between independant points). The $l = 18$ distribution (blue) is very close to a Gaussian (deviations are due to large scale gradients). However, the $l = 3$ pixel one (red) has wings that show up for large increments. These wings, are interpreted as a signature of intermittency, and in this context are associated to bursts of viscous dissipation.

3.3 Large shear filaments

Fig. 2 (middle panels) presents the resulting maps of CVIs, computed for a 3-pixel lag, on the ^{12}CO(1-0) data (top), and expressed in km s^{-1}. The large CVIs form filaments of aspect ratio as high as 10. These filaments are those points populating the wings in the PDF (left). They are poorly correlated with the ^{13}CO emission. On the contrary, the spatial correlation of large CVIs with the optically thin ^{12}CO emission (see Fig. 1 and bottom panel in Fig. 2) is striking. The optically thin ^{12}CO filaments are therefore the sites of the largest velocity shear.

3.4 Coherence from small to large scales

We applied the same procedure to large scale data obtained with coarser spatial resolution (Bensch et al. 2001). The resulting CVIs (Fig. 2, right panel) computed for a small lag (3 pixels) again shows filaments, extending over 1 parsec or more. Interestingly, the most prominent shear-filament located in the middle West extends the small one found in the 30m data set. The south-western filament at large scale might also be connected to the small one found in our maps. It is however not possible to ascertain whether these large scale filaments also correspond to warm and tenuous molecular gas.

These two datasets, treated in similar ways, show that the regions of largest velocity shear are high-aspect ratio (> 20) filaments coherent over the parsec scale , despite the fact that the molecular flow is turbulent.

4 Discussion and summary

The computation of the CVIs, at both small and large scales, show that for small lags, *i)* the PDF of CVI is not Gaussian at small scale, a possible signature of intermittency, *ii)* the points populating the non-Gaussian wings of the PDF are distributed into filaments, *iii)* these filaments are warm and tenuous molecular gas and *iv)* these filaments remain coherent over more than 1 pc. In this particular field, we also found that the orientations of the filaments might be related to that of the magnetic fields. This suggests that magnetic field may be strong enough to imprint their configuration on the gas structure.

The spatial correlation between the warm optically thin ^{12}CO(1-0) filaments and the regions of large velocity shear suggest that these structures are sites of burst of viscous dissipation which may be the heating source. Further non-equilibrium chemical modelling of HCO^+(1-0) observations in these structures does indeed stress the importance of viscous and ion-neutral–drift heating (Falgarone et al. 2005).

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