Intermittency of interstellar turbulence: extreme velocity-shears and CO emission on milliparsec scale[★]

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ABSTRACT

Aims. The condensation of diffuse gas into molecular clouds and dense cores occurs at a rate driven largely by turbulent dissipation. This process still has to be caught in action and characterized.

Methods. We observed a mosaic of 13 fields with the IRAM-PdBI interferometer (PdBI) to search for small-scale structure in the ¹²CO(1–0) line emission of the turbulent and translucent environment of a low-mass dense core in the Polaris Flare. The large size of the mosaic (1' × 2') compared to the resolution (4'') is unprecedented in the study of the small-scale structure of diffuse molecular gas.

Results. The interferometer data uncover eight weak and elongated structures with thicknesses as small as ≈3 mpc (600 AU) and lengths up to 70 mpc, close to the size of the mosaic. These are not filaments because once merged with short-spacings data, the PdBI-structures appear to be the sharp edges, in space and velocity-space, of larger-scale structures. Six out of eight form quasi-parallel pairs at different velocities and different position angles. This cannot be the result of chance alignment. The velocity-shears estimated for the three pairs include the highest values ever measured in regions that do not form stars (up to 780 km s^{−1} pc^{−1}). The CO column density of the PdBI-structures is in the range $N(\text{CO}) = 10^{14}$ to 10^{15} cm^{−2} and their H₂ density, estimated in several ways, does not exceed a few 10³ cm^{−3}. Because the larger scale structures have sharp edges (with little or no overlap for those that are pairs), they have to be thin layers of CO emission. We call them SEE(D)S for sharp-edged extended (double) structures. These edges mark a transition, on the milliparsec scale, between a CO-rich component and a gas undetected in the ¹²CO(1–0) line because of its low CO abundance, presumably the cold neutral medium.

Conclusions. We propose that these SEE(D)S are the first directly-detected manifestations of the intermittency of interstellar turbulence. The large velocity-shears reveal an intense straining field, responsible for a local dissipation rate several orders of magnitude above average, possibly at the origin of the thin CO layers.

Key words. ISM: evolution – ISM: kinematics and dynamics – ISM: molecules – ISM: structure – ISM: general – turbulence

1. Introduction

Turbulence in the interstellar medium (ISM) remains a puzzle in spite of dedicated efforts on observational and numerical grounds. This is because it is compressible, magnetized, and multi-phase, but also because of the huge range of scales separating those of injection and dissipation of energy. Moreover, because turbulence and magnetic fields are the main support of molecular clouds against their self-gravity, turbulent dissipation is a key process among all those eventually leading to star formation (see the reviews of [Elmegreen & Scalo 2004](#); [Scalo & Elmegreen 2004](#)).

In molecular clouds, turbulence is observed to be highly supersonic with respect to the cold gas. It is thus anticipated to dissipate in shocks in a cloud-crossing time (i.e. ≈ a few 10 Myr for giant molecular clouds of 100 pc with internal velocity dispersion of a few km s^{−1}). Magnetic fields do not significantly slow the dissipation down ([Mac Low et al. 1998](#)). Actually, this

is the basis of the turbulent models of star formation ([Mac Low & Klessen 2004](#)) – one of the two current scenarii of low-mass star formation – in which self-gravitating entities form in the shock-compressed layers of supersonic turbulence.

However, while it is unquestionable that the ISM is regularly swept by large-scale shock-waves triggered by supernovae explosions that partly feed the interstellar turbulent cascade ([Joung & Mac Low 2006](#); [de Avillez & Breitschwerdt 2007](#)), the smallest scales, barely subparsec in these simulations, are still orders of magnitude above the smallest observed structures and are unlikely to provide a proper description of the actual dissipation processes. Whether turbulent dissipation occurs primarily in compressive (curl-free) or in solenoidal (divergence-free) modes in the interstellar medium has therefore to be considered as an open issue.

An ideal target to study turbulent dissipation is the diffuse molecular gas because it is the component in which dense cores form, with less turbulent energy density than their environment. The word “diffuse” here comprises all material in the neutral ISM at large that is not in dense cores i.e. whose total hydrogen column density is less than a few 10²¹ cm^{−2}. This

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includes the mixture of cold and warm neutral medium (CNM and WNM), the edges of molecular cloud complexes (also called translucent gas), and the high latitude clouds. Diffuse gas builds up a major mass fraction of the ISM. Actually, on the 30 pc scale, [Goldsmith et al. \(2008\)](#) find that half the mass of the Taurus-Auriga-Perseus complex lies in regions having H_2 column density below $2.1 \times 10^{21} \text{ cm}^{-2}$.

Turbulent dissipation may also provide clues to the “out-standing mysteries” raised by observations of diffuse molecular gas (see the review of [Snow & McCall 2006](#)): the ubiquitous small scale structure, down to AU-scales ([Heiles 2007](#)), the remarkable molecular richness found in this hostile medium, weakly shielded from UV radiation (e.g. [Liszt & Lucas 1998](#); [Gredel et al. 2002](#)), the bright emission in the H_2 pure rotational lines exceeding the predictions of photon-dominated region (PDR) models ([Falgarone et al. 2005](#); [Lacour et al. 2005](#)), the ^{12}CO small-scale structures with a broad range of temperatures, H_2 densities and linewidths that preclude a single interpretation in terms of cold dense clumps ([Ingalls et al. 2000, 2007](#); [Heithausen 2004, 2006](#); [Sakamoto & Sunada 2003](#)).

The present paper extends the investigation of turbulence down to the mpc-scale in the translucent environment of a low-mass dense core of the Polaris Flare. Over the years, this investigation has progressed along three complementary directions:

- (i) A two-point statistical analysis of the velocity field traced by the ^{12}CO line emission, and conducted on maps of increasing size. Using numerical simulations of mildly compressible turbulence, [Lis et al. \(1996\)](#) and [Pety & Falgarone \(2003\)](#) first proposed that the non-Gaussian probability distribution functions (*pdfs*) of line centroid velocity increments (CVI) be the signatures of the space-time intermittency of turbulence¹ because the extrema of CVI (E-CVI) trace extrema of the line-of-sight average of the modulus of the plane-of-the-sky (*pos*) vorticity. Statistical analysis conducted on parsec-scale maps in two nearby molecular clouds have revealed that these extrema form parsec-scale coherent structures ([Hily-Blant et al. 2008](#); [Hily-Blant & Falgarone 2009](#), resp. Paper III, HF09).
- (ii) A detailed analysis (density, temperature, molecular abundances) of these coherent structures, based on their molecular line emission. The gas there is more optically thin in the ^{12}CO lines, warmer and more dilute than the bulk of the gas ([Hily-Blant & Falgarone 2007](#), hereafter Paper II), and large HCO^+ abundances, unexpected in an environment weakly shielded from UV radiation, have been detected there ([Falgarone et al. 2006](#), Paper I).
- (iii) Chemical models of non-equilibrium warm chemistry triggered by bursts of turbulent dissipation ([Joulain et al. 1998](#)). The most recent progresses along those lines include the chemical models of turbulent dissipation regions (TDRs) by [Godard et al. \(2009\)](#) and their successful comparison to several data sets, among which new submillimeter detections of $^{13}\text{CH}^+(1-0)$ (Falgarone et al., in preparation).

¹ Intermittency here refers to the empirical property of high Reynolds number turbulence to present an excess of rare events compared to Gaussian statistics, this excess being increasingly large as velocity fluctuations at smaller and smaller scales are considered (see the review of [Anselmetti et al. 2001](#)). Although the origin of intermittency is still an open issue (but see [Mordant et al. 2002](#); [Chevallard et al. 2005](#); [Arnéodo et al. 2008](#)), it is quantitatively characterized by the anomalous scaling of the high-order structure functions of the velocity and the shape of non-Gaussian *pdfs* of quantities involving velocity derivatives (e.g. [Frisch 1995](#)).

Fig. 1. The location of the 13-field mosaic observed at the Plateau de Bure interferometer (centered at RA = 01:55:12.26 and Dec = 87:41:56.30) is shown as the box on top of the integrated emission of the ^{12}CO and ^{13}CO ($J = 1-0$) maps obtained at the IRAM-30m. This is a place of low, almost featureless, CO line brightness. The arc-like structure visible in ^{13}CO traces the outer layers of the low-mass dense core. Contour levels are shown in the wedges.

The $^{12}\text{CO}(J = 2-1)$ observations of the Polaris Flare with unprecedented angular resolution and dynamic range are the first to evidence the association between extrema of CVI and observed velocity-shears² (HF09). No shock signature (density and/or temperature enhancement, SiO detection) has been found in the coherent structure of E-CVI identified in the Polaris Flare (Hily-Blant and Falgarone, in preparation). All the above suggest (but does not prove yet) that the coherent structures carrying the statistical properties of intermittency are regions of intense velocity-shears where dissipation of turbulence is concentrated.

The $^{12}\text{CO}(1-0)$ observations reported in this paper have been performed in a field located on one branch of the Polaris Flare E-CVI structure, in the translucent and featureless environment of a dense core (Fig. 1). The outline of the paper is the following: the observations and data reduction are described in Sect. 2. The observational results are given in Sect. 3. The characterization of the emitting gas is made in Sect. 4 and we discuss, in Sect. 5, the possible origin and nature of the CO structures that we have discovered. Section 6 puts our results in the broad perspective provided by other data sets and Sect. 7 compares them to chemical model predictions and numerical simulations of turbulence. The conclusions are given in Sect. 8.

2. IRAM Plateau de Bure Interferometer observations

We used the IRAM Plateau de Bure Interferometer (PdBI) to image, at high angular resolution and in the ^{12}CO ($J = 1-0$) line, a region of $\sim 1' \times 2'$ in the translucent environment of a dense core in the Polaris Flare ([Heithausen 1999](#); [Heithausen et al. 2002](#)). The location of the target field is shown in Fig. 1 as a rectangle on larger scale, single-dish maps of integrated $^{12}\text{CO}(J = 1-0)$ and $^{13}\text{CO}(J = 1-0)$ emission from ([Falgarone et al. 1998](#), hereafter F98). The average column density in this region ($\sim 10^{21} \text{ cm}^{-2}$) is about 100 times smaller than in the central parts of the dense core ($\sim 10^{23} \text{ cm}^{-2}$), 3 arcmin westwards. The average integrated ^{13}CO intensity over the mosaic area is weak $W(^{13}\text{CO}) = 2 \text{ K km s}^{-1}$.

² We use velocity-shear rather than velocity-gradient because the observations provide cross-derivatives of the velocity field, i.e. the displacement measured in the plane-of-the-sky (*pos*) is perpendicular to the line-of-sight velocity.

Table 1. Observation parameters. The projection center of all the data displayed in this paper is: $\alpha_{2000} = 01^{\text{h}}55^{\text{m}}12.26^{\text{s}}$, $\delta_{2000} = 87^{\circ}41'56.30''$.

Molecule	Transition	Frequency GHz	Instrument	Config.	Beam arcsec	PA °	Vel. Resol. km s ⁻¹	Int. Time hours	Noise K
¹² CO	(J = 1–0)	115.271195	PdBI	C&D	4.4 × 4.2	80	0.1	65.2/180 ^a	0.23 ^b
		115.271195	30m	—	21.3	0	0.1	—/—	0.40
¹³ CO	(J = 1–0)	110.201354	30m	—	22.3	0	0.1	—/—	0.19

^a Two values are given for the integration time: the 5 antennae array equivalent on-source time and the telescope time.

^b The noise value quoted here is the noise at the mosaic phase center.

2.1. Observations

The observations dedicated to this project were carried out in 1998 and 1999 with the IRAM interferometer at Plateau de Bure in the C and D configurations (baseline lengths from 24 m to 161 m). One correlator band of 10 MHz was centered on the ¹²CO (J = 1–0) frequency to cover a ~ 23 km s⁻¹ bandwidth with a channel spacing of 39 kHz, i.e. ~ 0.1 km s⁻¹. Four additional correlator bands of 160 MHz were used to measure the 2.6 mm continuum over the 500 MHz instantaneous IF-bandwidth then available.

We observed a 13-field mosaic centered on $\alpha_{2000} = 01^{\text{h}}55^{\text{m}}12.26^{\text{s}}$, $\delta_{2000} = 87^{\circ}41'56.30''$. The field positions followed a compact hexagonal pattern to ensure Nyquist sampling in all directions and an almost uniform noise over a large fraction of the mosaic area (see Fig. A.1 of Appendix A). The imaged field-of-view is about a rectangle of dimension of $85'' \times 130''$ oriented at a position-angle of 15° (because the (RA, Dec) PdBI field was selected in maps made in (*l*, *b*) coordinates).

Polaris being a circumpolar source, this project was a good time-filler. It was thus observed at 22 different occasions, giving a total of about 180 hours of *telescope* time with most often 3 or 4 antennas and rarely 5 antennas. Taking into account the time for calibration and data filtering this translates into *on-source* integration time of useful data of 65.2 h for a full 5-antenna array. The typical 2.6 mm resolution of these data is $4.3''$. The data used to produce the missing short-spacings are those of the IRAM key-program, fully described in F98 (see also Table 1).

2.2. Data reduction

The data processing was done with the GILDAS³ software suite (Pety 2005). Standard calibration methods implemented in the GILDAS/CLIC program were applied using close bright quasars as calibrators. The calibrated *uv* tables were processed through an Hanning filter which spectrally smoothed the data (to increase the intensity signal-to-noise ratio) while keeping the same velocity/frequency channel spacing.

All other processing took place into the GILDAS/MAPPING software. Following Gueth et al. (1996), the single-dish map from the IRAM-30m key program were used to create the short-spacing visibilities not sampled at the Plateau de Bure. These were then merged with the interferometric observations. Two different sets of *uv* tables (i.e. with and without short-spacings) were then imaged using the same method. Each mosaic field was imaged and a dirty mosaic was built combining those fields in the following optimal way in terms of signal-to-noise ratio (Gueth 2001)

$$J(\alpha, \delta) = \sum_i \frac{B_i(\alpha, \delta)}{\sigma_i^2} F_i(\alpha, \delta) \left/ \sum_i \frac{B_i(\alpha, \delta)^2}{\sigma_i^2} \right.$$

³ See <http://www.iram.fr/IRAMFR/GILDAS> for more information about the GILDAS softwares.

In this equation, $J(\alpha, \delta)$ is the brightness distribution in the dirty mosaic image, B_i are the response functions of the *i* primary antenna beams, F_i are the brightness distributions of the individual dirty maps and σ_i are the corresponding noise values. As may be seen in this expression, the dirty intensity distribution is corrected for primary beam attenuation, which makes the noise level spatially heterogeneous. In particular, noise strongly increases near the edges of the field of view. To limit this effect, both the primary beams used in the above formula and the resulting dirty mosaics are truncated. The standard level of truncation is set at 20% of the maximum in MAPPING.

Deconvolution methods were different for both data sets (i.e. with and without short-spacings). The dirty image of the PdBI-only data was deconvolved using the standard Clark CLEAN algorithm. One spatial support per channel map was defined by selecting positive regions on the first clean image which was obtained without any constraint. This geometrical constraint was then used in a second deconvolution. While it can bias the result, this two-step process is needed when deconvolving interferometric observations of extended sources without short-spacings. Indeed, the lack of short-spacings implies (among other things) a zero valued integral of the dirty beam and dirty image, which in turn perturbs the CLEAN convergence when the source is extended because the algorithm searches as many positive as negative CLEAN components. The only way around is to guide the deconvolution by the definition of a support where the signal is detected. On the other hand, the deconvolution of the combined short-spacings and interferometric *uv* visibilities can process blindly (i.e. without the possible bias of defining a support where to search for CLEAN components). This is what has been done and the good correlation of the structures seen in the deconvolved images of the data with and without short-spacings (see Figs. 4 and 5) gives us confidence in our deconvolution of the PdBI-only data.

The two resulting data cubes (with and without short-spacings) were then scaled from Jy/beam to T_{mb} temperature scale using the synthesized beam size (see Table 1). Final noise rms measured at the centered of the mosaic is about 0.23 K in both data cubes.

3. Observational results

3.1. PdBI structures: sharp edges of extended structures

At the adopted cloud distance of $d = 150$ pc, $1''$ corresponds to 0.75 mpc or 150 AU, so that the spatial resolution of the PdBI data is 3.2 mpc or 660 AU.

The integrated emission detected with the PdBI is displayed in Fig. 2 (left panel), with the corresponding signal-to-noise ratio (right panel). The integrated emission covers most of the mosaic area. This is no longer true when this emission is displayed in velocity slices (Fig. 3, top panels). Several distinct structures are detected in addition to the bright CO peak, at

Fig. 2. Map of integrated emission of the PdBI data (top left), and signal-to-noise ratio (top right) for the ^{12}CO ($J = 1-0$) line. Same for the 3 mm continuum emission (bottom panels). The synthesized beam is shown in the bottom left inserts.

velocities $[-3.1, -2.3] \text{ km s}^{-1}$. Most are weak (the first level in the PdBI channel maps of Fig. 3 is 3σ) but they extend over many contiguous synthesized beams (10 to 30).

The PdBI data merged with the short-spacings provided by the 30m telescope and the $^{12}\text{CO}(1-0)$ emission detected by the IRAM-30m telescope are displayed in the same velocity-slices, for comparison, in Fig. 3, central and bottom panels respectively. Most of the structures seen by the PdBI lie at the edge in space and in velocity space of extended emission present in the single-dish channel maps. This property is most visible for the two structures in the north-west of the mosaic over $[-4.8, -4.4] \text{ km s}^{-1}$ and $[-2, -1.2] \text{ km s}^{-1}$, and in the central region at $v = -2.8 \text{ km s}^{-1}$. It is even better seen by comparing the single-dish maps before and after combination with the PdBI data. The single-dish maps are changed in two-ways: the structures exhibit sharper, more coherent boundaries and these boundaries extend further in velocity-space (e.g. channels -4.7 and -2.3 km s^{-1}). In a given channel of width Δv_c , the size of the detected structures in the CO emission Δx_c is inversely proportional to the velocity-shear, $\Delta x_c = \Delta v_c / (\partial v_{\text{LSR}} / \partial x_{\text{pos}})$. Hence, the detection of small-scale structures at the edge of the velocity coverage of larger-scale structures may be favored by an increase of the velocity shear at these edges.

The fact that these structures appear both in PdBI-only data and in combined (PdBI+30m) data gives confidence in their reality, independently of the deconvolution techniques.

In summary, the interferometer is sensitive by construction to small-scale (i.e. sharp) variations of the space-velocity CO distribution. It happens that the sharp structures detected by the interferometer lie at the edge in space and velocity of regions of shallow CO emission that extend over at least arcminutes, as displayed in the 30m channel maps. The PdBI-structures are therefore the sharp edges of extended structures.

3.2. Observed characteristics of the PdBI structures

We have identified eight structures in the space-velocity $^{12}\text{CO}(J = 1-0)$ PdBI data cube that are well separated from one another in direction and in velocity. They are shown in Fig. 4, each drawn over its proper velocity range. The right panels show the PdBI data combined with 30m data over the same velocity ranges to further illustrate that the PdBI filtering emphasizes the sharpness of the edge of the space-velocity structures. Figure 4 also shows that the single-dish structures cover a large fraction of the mosaic area. For instance, in the case of structure #1, the single-dish structure extends over the whole southern half of the mosaic, while for structure #5 it almost covers the northern half.

The observed properties of the 8 PdBI structures are given in Table 2. The peak $^{12}\text{CO}(J = 1-0)$ temperature is that detected by the PdBI, therefore the excess above the extended background, resolved out by the PdBI. The size $\theta_{1/2}$ is the half-power thickness of the elongated structures, deconvolved from the beam size. The projected thickness, in mpc, is called $l_{\perp}$ by opposition to the unknown depth along the line-of-sight ($l_{\parallel}$), called $l_{\parallel}$. The position-angle PA is that of the direction defined, within $\pm 10^\circ$, by the three brightest pixels of each structure. When they are not aligned, as in the case of #8, we determine a direction with the meaning of a least-square fit. It corresponds to an average PA over the detected structure that does not take into account the substructure visible in Fig. 6 for instance. Because of their different velocity width and CO line temperature, the CO integrated brightness of the eight structures varies by a factor 25.

Most of the PdBI-structures are elongated and straight with different position-angles in the sky. Interestingly, they do not shadow each other in space and in velocity space (i.e. each fills only a small area of the mosaic in a small velocity interval, and the positions and areas of the detected structures are different). Their cumulative surface filling factor in the mosaic field is large, $f_s \approx 0.5$ (Fig. 2), i.e. $f_s = 0.6$ for the structures detected at more than 1-sigma and $f_s = 0.3$ for 3-sigma detections. However, the fraction of the single-dish power (integrated over the mosaic) seen by the PdBI in the $^{12}\text{CO}(1-0)$ line is low. It depends on the velocity interval: it varies between 2% in the ^{12}CO line-core (defined as the velocity range, $[-5.0, -3.5] \text{ km s}^{-1}$, over which the single-dish $^{13}\text{CO}/^{12}\text{CO}$ is the largest, see F98), and 6% in the line-wings. Figure 5 displays the emission profile of the 8 PdBI-structures with the single-dish ^{12}CO and $^{13}\text{CO}(J = 1-0)$ emissions over the same area (defined by the polygons of Fig. 4).

Last, the PdBI-structures cover the full velocity range of the single-dish CO line (see bottom panel of Fig. 5) including the far line-wings (e.g. structure #2 at -5.5 km s^{-1}). Note however that the spectrum integrated over the whole mosaic peaks at -3 km s^{-1} , in the wing of the single-dish ^{12}CO line while its minimum, around -4.5 km s^{-1} , coincides with the peak of the single-dish ^{13}CO line (i.e. line core). The broad velocity distribution of the PdBI-structures within the single-dish line coverage ensures that they are not artefacts of radiative transfer. If they were, they would appear preferentially at extreme velocities because CO photons escape probability is larger there. There may be a small effect since the power fraction in the line-wings is slightly larger than in the line-core, but these fractions are a few percent in each case. The structures found are therefore real edges in space and velocity-space of larger structures.

In this respect, it is interesting to place each PdBI-structure in its $^{12}\text{CO}(1-0)$ larger-scale environment at the appropriate velocity (Fig. 8). The PdBI-structures, marked as polygons, lie at the edge of structures that extend beyond the field of the mosaic,

Fig. 3. From top to bottom, maps of the PdBI, PdBI+30m and 30m of $^{12}\text{CO}(1-0)$ emission integrated over the same velocity slices of 0.3 km s^{-1} centered as indicated.

up to $\sim 300''$ or 0.2 pc . In the case of structures #3, #4 and #5, the orientation of the edges of the large-scale patterns is more visible

in the $^{13}\text{CO}(1-0)$ maps (Fig. 9), likely because of the $^{12}\text{CO}(1-0)$ optical depth. This coincidence strongly suggests that the

Table 2. Spatial and kinematic characteristics of the ^{12}CO PdBI-only structures.

Structure	$v_{\min}$ km s^{-1}	$v_{\max}$ km s^{-1}	$\Delta v_{1/2}$ km s^{-1}	T_{peak} K	$W(\text{CO})$ K km s^{-1}	$\theta_{1/2}$ arcsec	$l_{\perp}^a$ mpc	PA $^{\circ}$	$n_{\text{H}_2}^{\text{max } b}$ cm^{-3}
1	-5.7	-5.2	0.1	0.6	0.06	4	3.0	109	1000
2	-5.6	-5.4	0.2	1.8	0.36	10	7.5	173	2400
3	-5.2	-4.8	0.2	2.4	0.48	9	6.8	62	3200
4	-4.3	-4.1	0.1	1.2	0.12	8	6.0	59	1000
5	-3.4	-2.6	0.4	4	1.6	12	9.0	91	8900
6	-3.4	-2.6	0.25	1.2	0.3	10	7.5	161	2000
7	-3.2	-3.0	0.15	1.2	0.18	15	11.3	173	800
8	-1.7	-1.3	0.15	1.2	0.18	9	6.8	59	1200

^a Projected thickness of the filamentary structures deconvolved from beam size; ^b upper limit because computed as $n_{\text{H}_2} = N(\text{H}_2)/l_{\perp}$ instead of using $l_{\parallel}$ with $N(\text{H}_2)$ derived from $W(\text{CO})$ (see text).

Fig. 4. The 8 structures described in Table 1. *Left panels:* PdBI-only $^{12}\text{CO}(1-0)$ emission integrated over the indicated velocity interval appropriate to each structure. *Right panels:* same for the combined PdBI+30m mission. The polygons show the area over which the CO spectra of Fig. 5 are computed.

Fig. 5. Comparison of spectra integrated over either the polygons defined in Fig. 4 and the whole mosaic. The ^{12}CO and ^{13}CO ($J = 1-0$) single-dish spectra are shown resp. in light and darker grey, while the PdBI only ^{12}CO ($J = 1-0$) spectra is shown in black. ^{13}CO amplitude have been multiplied by a factor of two and PdBI only ^{12}CO amplitude by a factor of 10. Note that *i*) only a small fraction of the single-dish flux is recovered at PdBI and *ii*) the centroid velocities of the small-scale structures are all, but one, outside that of the ^{13}CO peak.

orientation of the PdBI-structures is not only real but also rooted in the larger-scale environment.

3.3. Pairs of parallel structures

One of the most challenging finding of this study is the fact that among the eight elongated PdBI-structures, six form 3 close pairs (separated by less than $20''$ in projection) of structures parallel within $\pm 10^\circ$ (Table 2 and Fig. 4). These are the pairs of structures [#3, #8], [#1, #5] and [#6, #7]. The average

position-angles of each pair $\overline{\text{PA}} = 60, 100$ and 168° are all different. Since the structures (at least in the two first pairs) are at different velocities, they are not due to artefacts of the deconvolution process.

The probability of a chance association of these three pairs in the field of the mosaic is estimated to be at most 4×10^{-9} . It is the cube of the probability of having one close pair of parallel structures. The latter is the product of the probability, equal to 5.4×10^{-3} , that two, out of eight, randomly oriented straight structures be aligned within $\pm 10^\circ$ of each other (i.e. be together in a

Fig. 6. Structures #3 at -5 km s^{-1} and #8 at -1.5 km s^{-1} overplotted (resp. black and red contours) to display their close spatial correlation.

solid angle $\Delta\Omega = 0.1 \text{ sr}$, by that (ranging between 0.2 and 0.3 depending on the orientation of the pair) to be separated in projection by less than $20''$ in a mosaic of $1' \times 2'$. The probability of a chance association is only slightly underestimated if one considers the structure #8 that is not straight, strictly speaking.

Since the probability of a chance association of the observed pairs is so low, we infer that the pairs are real associations. This physical connexion is supported by the detail of the spatial distribution of the ^{12}CO emission integrated over the two velocity ranges of structures #3 and #8 in Fig. 6: the hole, in the low-velocity emission is filled in by high-velocity emission, while a common average orientation exists over $\sim 1'$ for the pair.

Two position-velocity cuts (Fig. 7) across the pair [#3, #8] further illustrate what is meant by sharp edges and real association. The cut across the PdBI-only data cube (left panel) shows two CO peaks centered at offset positions $40''$ (resp. $46''$) and velocities -4.9 km s^{-1} (resp. -1.6 km s^{-1}) for the low- and high-velocity component respectively. These resolved peaks are located exactly at the terminal pixels of the larger-scale structures visible at the same velocities in the cut across the PdBI+30m data cube (right panel). On this cut, the low-velocity component may be followed over all offsets below $\approx 46''$, while the high-velocity component is visible at all offsets above $\approx 40''$. This cut also illustrates a clear difference between the two velocity components: the velocity of structure #3 (peak at -5 km s^{-1} in the PdBI spectrum of Fig. 5) falls within the velocity coverage of the bright extended gas (^{12}CO and ^{13}CO line core in the single-dish spectra) while that of structure #8 (peak at -1.5 km s^{-1} in the PdBI spectrum of Fig. 5) is not blended with any other emission in that extreme velocity range and appears as a weak emission in the single-dish spectrum (i.e. a line-wing). Such blendings in space and velocity projections with extended components resolved out by the PdBI observations (Fig. 7, right panel) explain why such pairs of structures are so difficult to recognize in single-dish observations or low sensitivity interferometric observations.

The PdBI-structures cannot therefore be understood as isolated entities. Not only are they the sharp edges of larger CO-structures seen in the single-dish maps but also 6 out of 8 of these edges are paired. In the following, we will call the CO extended structures bounded by sharp edges either sharp-edged extended structures (SEES) or sharp-edged extended double

structures (SEEDS) when they belong to a pair, to emphasize this essential property.

3.4. Velocity shears

The pairs being real associations, we ascribe a velocity-shear to each of them. The projected separation $\delta l_{\perp}$ and velocity difference δv_{LSR} between the low- and high-velocity components of each pair provide a measure of the velocity-shear $\delta v_{\text{LSR}}/\delta l_{\perp}$. We cannot determine whether this measure is a lower or upper limit of the true velocity-shears because of the projection effects: both the separation measured in the *pos* and the velocity difference are lower limits.

The results are given in Table 4. The method used is illustrated in Fig. 7 (left panel) for the pair [#3, #8]: the projected separation between the low- and high-velocity components is $6''$ or 4.5 mpc while the velocity separation is 3.5 km s^{-1} , hence a velocity-shear of $777 \text{ km s}^{-1} \text{ pc}^{-1}$, the largest ever measured in CO emission in a molecular cloud devoid of star formation activity. These values correspond to an average over several positions along the shear direction, including those where the two velocity components partially overlap. The separation is therefore slightly underestimated by the averaging. Note that one pair only, [#6, #7], has a very small velocity-shear, probably because, in that case, the two velocity components involved in the shear are mostly in the *pos*. A rate-of-strain, defined as $a = \frac{1}{2} \delta v_{\text{LSR}}/\delta l_{\perp}$, and timescale $\tau = a^{-1}$, are also given to help comparison with chemical models (Sect. 7). The large observed velocity-shears translate into timescales as short as a few 10^3 yr , if the Lagrangian and Eulerian views of the fluid can be exchanged (see Mordant et al. 2002).

3.5. The SEE(D)S are layers of CO emission

The small-scale structures detected by the PdBI have properties never seen before because the present observations are most sensitive and the field of view is large in comparison to the resolution: (1) they are not clumps, but elongated structures, only bounded by the limited size of the mosaic; (2) they all mark a sharp fall-off of the CO emission in selected velocity ranges: they are not isolated filaments, but the sharp edges (3 to 11 mpc in projection), simultaneously in space and velocity-space, of larger structures, the SEE(D)S, extending beyond the mosaic ($l > 0.2 \text{ pc}$); (3) six of these form three pairs of parallel structures at different velocities, with a small projected separation and the velocity-shears estimated for two of these pairs, several $100 \text{ km s}^{-1} \text{ pc}^{-1}$, are the largest ever measured in non-star forming clouds.

If the SEE(D)S were CO-emitting volumes (i.e. 3-dimensional structures in space) of characteristic dimension l , their edges would be surfaces commensurate with l^2 . In projection, these edges would appear as surfaces, also commensurate with l^2 for a random viewing angle. Only if these surfaces were plane and viewed edge-on (within $\pm 5^\circ$ for a projected size less than one tenth of their real size) would these edges appear as thin elongated structures. We rule this out on statistical grounds: the mere fact that we detect 8 sharp CO-edges in the small field-of-view of the PdBI observations suggests that it is not a rare configuration and that the eight sharp CO-edges are seen from random viewing angles. We thus infer that the SEE(D)S are CO-layers, rather than volumes and that their thickness is $\sim 10 \text{ mpc}$ or less, on the order of the width of the PdBI-structures.

Fig. 7. Position-velocity diagrams across the pair of structures [#3, #8]. *Left:* cut across the PdBI-only map. *Center:* rotated PdBI channel-map $[-1.7, -1.3]$ km s^{-1} , showing the direction and distance (horizontal size of the box) over which the CO emission is averaged for the cut. The cut runs from the southern to northern edge of the box. *Right:* same across the PdBI+30m data cube.

Fig. 8. Integrated maps of the same velocity range as that defined in Fig. 4 of the ^{12}CO ($J = 1-0$) emission observed at the IRAM-30m. Green crosses delimit the mosaic position and the red polygon as defined in Fig. 4 shows the position of the elongated structures detected at PdBI.

Fig. 9. Same as Fig. 8 except that the single dish map is that of ^{13}CO ($J = 1-0$).

This statistical argument is reinforced by the presence of pairs. The SEEDS are structures that have sharp edges with only small or null overlaps. If their interface were 2-dimensional (i.e. if the SEEDS were volumes), the small overlap would occur only for an edge-on viewing, an unlikely case. Their interface is therefore 1-dimensional rather than 2-dimensional and the SEEDS are layers of CO emission. This ensures that under any viewing angle the two extended velocity components are detected with only a narrow or null spatial overlap in projection. The SEEDS could still be 3-dimensional pure velocity-structures, where large velocity-shears produce sharp edges in channel maps of finite spectral resolution (see Sect. 3.1). However, with the same statistical argument as above, concerning density structures, we rule out the possibility that the SEEDS be 3-dimensional velocity structures. These must be CO layers.

In summary, the sharpness of the edges of the SEE(D)S, associated with the fact that we detect 8 cases in the mosaic and three close-pairs that do not overlap in space, implies that the SEE(D)S are thin layers of CO emission rather than volumes.

4. Gas density of the PdBI-structures

4.1. Estimates from CO line emission

Because of the elongated shape of most of the structures and the fact that they are edges of more extended emission, we have not tried to decompose the observed emission using clump finding algorithms such as GAUSSCLUMP (Stutzki & Guesten 1990). We estimate below the gas density in these structures in two independent ways and compare the results to those inferred from the dust continuum emission.

First, we compute upper limits of the H_2 densities (Table 2) by adopting the CO-to- H_2 conversion factor $X = 1.56 \pm 0.05 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ (Hunter et al. 1997) so that $n_{H_2} = 5 \times 10^4 \text{ cm}^{-3} W(\text{CO})/l_{\text{mpc}}$, for a *los* depth equal to the projected thickness $l_{\perp}$. Since we are observing edges of layers (see Sect. 3.2), the inferred densities are overestimated by the unknown factor $l_{\parallel}/l_{\perp}$. The upper limits of the H_2 densities derived from the galactic CO to H_2 conversion factor (Table 2) vary by a factor 10 only.

Alternatively, one may use a LVG analysis to estimate the gas properties in these structures. Two assumptions are made: (1) the CO emission is not beam-diluted and (2) the excitation is assumed to be the same as measured in the same field with the IRAM-30m so that we adopt the line ratio $R(2-1/1-0) = 0.7 \pm 0.1$ (Falgarone et al. 1998; Hily-Blant et al. 2008). This value may be representative of the excitation of translucent molecular gas because the same line ratio is found in different observations sampling a similar kind of molecular gas (Pety et al. 2008). Under these conditions, the CO column densities per unit velocity are very well determined for all line temperatures. They are given in Table 4 for the brightest, weakest, and most common CO peak temperature observed. The inferred CO column densities differ by only a factor 10 to 16 between the brightest and weakest structure.

Table 4 also gives the range of gas kinetic temperatures and associated range of densities, thermal pressures P_{th}/k and CO abundances of possible solutions. The range of temperatures is bounded towards high values by the thermal width of the CO lines ($T_k < 250 \text{ K}$ for the broadest line, $< 35 \text{ K}$ for the narrowest). Solutions colder than 10 K are unlikely because the gas is poorly shielded from the ambient ISRF. The CO optical depth is therefore smaller than a few, in agreement with the results of Paper II. A similar conclusion has been derived by Heithausen (2006) after he failed to detect the ^{13}CO and $\text{C}^{18}\text{O}(J = 1-0)$

line with the PdBI in a nearby small-area molecular structure (SAMS) field.

Each set of H_2 density and kinetic temperature in the LVG solutions, corresponds to a product $X(\text{CO})l_{\parallel}$ where $X(\text{CO})$ is the CO abundance relative to H_2 . The range of CO abundances inferred from the LVG computations are given in Table 2 for $l_{\parallel} = l_{\perp}$. They may be overestimated by the unknown ratio $l_{\parallel}/l_{\perp}$.

Table 4 shows the range of possible H_2 densities derived from the LVG analysis for gas temperatures between 10 K and 200 K at most. The comparison of these values with the upper limits inferred from the CO-to- H_2 conversion factor (Table 2) provides narrower H_2 density ranges, $n_{H_2} = 800$ to 10^3 cm^{-3} , and 300 to $2 \times 10^3 \text{ cm}^{-3}$, for the weakest and most common structures respectively. In spite of all the uncertainties, the two methods infer consistent H_2 densities that do not exceed $3 \times 10^3 \text{ cm}^{-3}$. Moreover, whether the gas is cold or warm, its thermal pressure is about the same, within a factor of a few, and is in harmony with that inferred from carbon line observations in the local ISM that has an average of $P_{\text{th}}/k \sim 3 \times 10^3 \text{ K cm}^{-3}$ with fluctuations up to $\sim 10^5 \text{ K cm}^{-3}$ (Jenkins & Tripp 2007).

4.2. Estimates from the dust continuum emission

In addition to ^{12}CO lines, we have detected continuum emission. This emission is close to the noise level, except for the large bright spot associated to the ^{12}CO peak of emission. A comparison of the continuum emission with the CO contour levels (Fig. 2) suggests that the elongated feature of continuum emission in the north-western corner of the mosaic is also real.

On the basis of the coincidence of the peaks of the ^{12}CO and continuum emission in the mosaic, we ascribe the continuum emission to thermal dust emission. The average continuum brightness over the ^{12}CO peak (Fig. 2) is $2 \pm 1 \text{ mJy/beam}$, hence $I_{\text{cont}} = 1 \pm 0.5 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}$. The dust opacity, $\tau_d = I_{\text{cont}}/B_{\nu}(T_d)$, depends on the dust temperature. We adopt a dust emissivity $\tau_d = 8.7 \times 10^{-26} (\lambda/250 \mu\text{m})^{-2} N_H$, deduced from COBE data for dust heated by the ambient interstellar radiation field (ISRF) (Lagache et al. 1999). For $T_d = 10 \text{ K}$ and $\nu = 115 \text{ GHz}$, we find $\tau_d = 3.2 \times 10^{-7}$ and $N_H = 4.0 \times 10^{20} \text{ cm}^{-2}$ across the peak. For $T_d = 17 \text{ K}$, the most plausible value in translucent gas of the Solar Neighborhood, this value would be lower by a factor 2 and for $T_d = 8 \text{ K}$ it would be larger by 40%, providing the range $N_H = 2.0 \times 10^{20}$ to $5.6 \times 10^{20} \text{ cm}^{-2}$ for high and low dust temperatures, respectively. This estimate of N_H may be compared to that inferred from ^{12}CO in the previous section. If we allow for a column density of atomic hydrogen comparable to that of H_2 , as found in the Polar Flare by Heithausen & Thaddeus (1990), the total H column density inferred from CO for the peak of structure #5 ranges between $N_H = 3N(H_2) = 2 \times 10^{19}$ to $2.4 \times 10^{20} \text{ cm}^{-2}$ for the warm and cold solutions respectively (assuming a size of 9 mpc). The two ranges of values would overlap for a depth a few times larger than the observed projected size, allowing for warm and moderate density solutions where the dust temperature is lower than that of the gas. Given the many uncertainties in the different steps (the questionable validity of the CO line analysis, the knowledge of dust emissivity and temperature), the consistency between these two independent estimates is encouraging and we are confident that we have detected the dust thermal emission of the brightest small-scale structure and that its H_2 density is not higher than a few 10^3 cm^{-3} .

Aside from the peak, the rest of the structures have column densities a few times smaller and their dust continuum emission

Table 3. Spatial and kinematic characteristics of the three pairs of parallel PdBI-only structures.

Pair	v_1 km s ⁻¹	v_2 km s ⁻¹	δv_{LSR} km s ⁻¹	$\delta l_{\perp}^a$ mpc	$\delta v/\delta l_{\perp}$ km s ⁻¹ pc ⁻¹	a^b s ⁻¹	τ^c yr	l^d mpc
#3, #8	-5.0	-1.5	3.5	4.5	777	1.3×10^{-11}	2.5×10^3	45
#1, #5	-5.4	-3.0	2.4	9.0	267	4.5×10^{-12}	4×10^3	45
#6, #7	-3.0	-3.1	0.1	16	6	10^{-13}	3×10^5	40

^a Averaged separation between the PdBI CO peaks; ^b $a = \frac{1}{2}\delta v/\delta l_{\perp}$; ^c $\tau = a^{-1}$; ^d length over which the structures are parallel within $\pm 10^\circ$.

Table 4. Results of LVG radiative transfer calculations for representative observed values (see Table 2).

	T_{peak} K	$N(\text{CO})/\Delta v^a$ cm ⁻² /km s ⁻¹	Δv km s ⁻¹	$N(\text{CO})$ cm ⁻²	T_k range K	n_{H_2} range ^b cm ⁻³	P_{th}/k range ^b K cm ⁻³	$X(\text{CO})$ range ^b $\times 10^{-5}$
brightest	4	$3\text{--}4 \times 10^{15}$	0.4	$1.2\text{--}1.6 \times 10^{15}$	10–200	$3 \times 10^3\text{--}250$	$3\text{--}5 \times 10^4$	2–20
most common	1.2	1.5×10^{15}	0.2	3×10^{14}	10–140	$8 \times 10^3\text{--}300$	$8\text{--}4 \times 10^4$	0.16–4
weakest	0.6	1.0×10^{15}	0.1	1.0×10^{14}	7–35	$1 \times 10^4\text{--}800$	$7\text{--}3 \times 10^4$	0.11–1.4

^a Assuming $R(2\text{--}1/1\text{--}0) = 0.7 \pm 0.1$; ^b the LHS (resp. RHS) values correspond to the lowest (resp. highest) gas temperature.

is expected to lie closer to the noise level. In addition, the surface filling factor of the ¹²CO structures being large in the central area of the mosaic, the PdBI visibility of the continuum emission of individual structures is expected to be highly reduced compared to that of the line which takes advantage of velocity-space. This may be the reason that the continuum emission and the ¹²CO emission do not coincide elsewhere: the continuum emission is more heavily filtered out by the interferometer than the ¹²CO emission.

5. What are the SEE(D)S?

5.1. Manifestations of the small-scale intermittency of turbulence

The two largest velocity-shears given in Table 3 are more than two orders of magnitude larger (within the uncertainties due to projections) than the average value of 1 km s⁻¹ pc⁻¹ estimated on the parsec scale in molecular clouds (Goldsmith & Arquilla 1985). The velocity field in these two SEEDS therefore significantly departs from predictions based on scaling laws obtained from ¹²CO(1–0) in molecular clouds, such as that shown in Fig. 10. In spite of a significant scatter of the data points, a power law $\delta v_l \propto l^{1/2}$ characterizes the increase of the velocity fluctuations with the size-scale l , at least above ~ 1 pc. Below that scale-length, the scatter increases and a slope 1/3 would not be inconsistent with the data. According to the former scaling, the velocity-shear should increase as $l^{-1/2}$, therefore by no more than $140^{1/2} = 12$ between 1 pc and 7 mpc. If the other scaling is adopted, this factor becomes $140^{2/3} = 26$. Now, the observed shears increase by more than two orders of magnitude between these two scales. This is conspicuous in Fig. 10 where the 8 PdBI-structures of Table 2 are plotted either individually or as pairs (i.e. as they would be characterized if the spatial resolution were poorer and individual structures were not isolated in space, providing for instance a linewidth $\Delta v_{1/2} = 3.5$ km s⁻¹ and a size $l_{\perp} \sim 7$ mpc for the pair [#3, #8]).

This result has to be put in the broader perspective described in Sect. 1. The statistical analysis of the velocity field of this high latitude cloud (Paper III, HF09) shows that the *pdf* of the ¹²CO line-centroid velocity increments increasingly departs from Gaussian as the lags over which the increments are measured decrease. The locus of the positions that populate the *pdf*

Fig. 10. Size-linewidth relation for a large sample of ¹²CO(1–0) structures (see Appendix B) to which are added: the SAMS data (single-dish data from Heithausen 2002, 2006 (solid triangles); PdBI data within SAMS2 Heithausen 2004 (open triangles)), a polygon that provides the range of values for the 12 structures of Sakamoto & Sunada (2003) and the eight structures of Table 2 (solid squares). The 3 empty squares without error bars show where the three pairs of PdBI-structures would be if not resolved spatially (i.e. the velocity increment between the two structures would appear as a linewidth for the pair). Same with the large triangle for the pair of structures in SAMS2. The straight lines show the slopes 1/3 and 1/2 for comparison.

non-Gaussian wings forms elongated and thin (~ 0.03 pc) structures that have a remarkable coherence, up to more than a parsec. HF09 propose, on this statistical basis, but also because of their thermal and chemical properties given in Sect. 1, that these structures trace the intermittency of turbulent dissipation in the field. The pair of structures [#3, #8] belongs to that locus of positions (see their Fig. 3). The extremely large velocity-shears measured in that small field are not just exceptional values: they have to be understood as a manifestation of the small-scale intermittency of interstellar turbulence, as studied on statistical grounds in a much larger field.

5.2. The emergence of CO-rich gas

The PdBI-structures mark sharp edges in the ^{12}CO emission. As discussed in Sect. 3.3 and illustrated in Fig. 7, the CO emission of space-velocity structures extending over arcminutes (the SEE(D)S) drops below the detection level over $4.3''$ (the resolution). Therefore, several questions arise: what is the nature of the undetected gas that provides the continuity of the flow? Is it undetected because its density is too low to excite the $J = 1-0$ transition of ^{12}CO ? Or is it dense enough but with too low a CO abundance? For simplicity, in the following discussion, “CO-rich” qualifies the gas with $X(\text{CO}) > 10^{-6}$, the CO abundance of the weakest detected structure (Table 4), and “CO-poor” the gas with a lower CO abundance.

According to LVG calculations, the 3σ detection limit of our observations allows us to detect CO column densities as low as $N(\text{CO}) \sim \text{a few } 10^{14} \text{ cm}^{-2}$ in gas as diluted as $n_{\text{H}} \sim 50 \text{ cm}^{-3}$, at any temperature, and for a velocity dispersion of 0.2 km s^{-1} , characteristic of the structures found. This detection limit is very low. Therefore, if the undetected gas on the other side of the edge is CO-rich (with a total hydrogen column density comparable to that of the detected part), it has to be at a density lower than $n_{\text{H}} \sim 50 \text{ cm}^{-3}$, not to excite the $^{12}\text{CO}(J = 1-0)$ transition at a detectable level. We rule out this possibility because this density is that of the CNM and it is unlikely that gas at that density be CO-rich (see also the models of Pety et al. 2008).

The alternative is that the undetected gas is CO-poor and that it is not its low density but its low CO abundance that makes it escape detection in $^{12}\text{CO}(J = 1-0)$. Given the sharpness of the edges of the SEE(D)S, between 3 and 11 mpc (Table 2), the process responsible for this transition has to be able to generate a significant CO enrichment over that small scale.

In the above, we rule out the possibility that the sharp edges (i.e. the PdBI-structures) mark photodissociation fronts, because the orientations of such fronts would not be randomly distributed, as is observed. Moreover, there is no source of UV photons in that high-latitude cloud and the radiation field there is the ambient galactic ISRF. Photodissociation fronts would not have different orientations depending on gas velocities varying by only a few km s^{-1} . The sharp edges are not either folds in layers of CO emission because those who belong to SEES (single structures) lack the second part of the layer, and those who belong to SEEDS have the two parts at different velocities.

We thus infer that the SEE(D)S are the outcome of a dynamical process, that involves large velocity-shears, and takes place in a gas undetected in $^{12}\text{CO}(1-0)$ emission, because it is CO-poor, not because it is too diluted. This gas may be the CNM and the dynamical process has to be able to enrich the CNM in CO molecules within a few 10^3 yr and over a few milliparsec.

6. Comparison with other data sets

Our results broaden the perspective regarding the existence of small-scale CO structures in molecular clouds. Heithausen (2002, 2004, 2006) has found small-area molecular structures (SAMS) that are truly isolated CO features in the high latitude sky. PdBI observations of the SAMS (Heithausen 2004) reveal bright sub-structures that are all brighter and broader than our PdBI-structures. Unfortunately, the emission has been decomposed into clumps, a questionable procedure because short-spacings have not been combined to the PdBI data and the CLEAN procedure tends to create structures on the beam scale. The large H_2 densities inferred are therefore likely overestimated. An interesting feature can be seen in the channel maps,

though. Two elongated thin patterns cross the field, reminiscent for their thickness and length of what is found in the present study. A velocity shear of $180 \text{ km s}^{-1} \text{ pc}^{-1}$ is estimated between these two elongated structures for a velocity separation of 0.9 km s^{-1} and a pos spatial separation of $10''$ on average (or 5 mpc at the assumed distance of 100 pc). This velocity-shear is thus commensurable with the two largest values found in the Polaris field.

Ingalls et al. (2007) have detected milliparsec clumps in a high latitude cloud. They are located in the line-wings of the CO single-dish spectrum and they model them as tiny (1–5 mpc) clumps of density of a few 10^3 cm^{-3} . A more detailed comparison with the present results is not possible because they do not analyze individual structures.

Sakamoto & Sunada (2003) have discovered a number of CO small-scale structures in the low-obscuration regions of long strip maps beyond the edge of the Taurus molecular cloud. Their main characteristics are their large line-width and their sudden appearance, and disappearance, within 0.03 to 0.1 pc. The authors interpret these features as the signature of structure formation induced by the thermal instability of the warm neutral medium (WNM) in the turbulent cloud envelope. These CO small-scale structures thus carry the kinematic signatures of the embedding WNM, hence their large velocity dispersion, both interclump and intraclump. The inferred line ratio, $R(2-1)/(1-0) = 0.4$, is low, consistent with a low excitation temperature and H_2 densities lower than $\sim 10^2 \text{ cm}^{-3}$. The authors propose that their small-scale CO structures pinpoint molecule-forming regions, driven by the thermal instability in the turbulent diffuse ISM.

Our data therefore share many properties with these different samples. Figure 10 allows a comparison of the projected size and linewidth of the above milliparsec-scale structures with those of $^{12}\text{CO}(1-0)$ structures identified in data cubes from non-star-forming regions of all sizes, up to several 100 pc (see the relevant references in Appendix B). Although some of them (a few individual PdBI-structures of our sample) further extend the general scaling law down to 2 mpc, most of them significantly depart from this law by a large factor. As already mentioned in Sect. 5.1, the departure is the largest for the pairs of PdBI-structures, as they would appear if they were not resolved spatially i.e. as anomalously broad structures with respect to their size. The increased scatter of velocity-widths of the structures below 0.1 pc down to 1 mpc may be seen as another manifestation of the intermittency of turbulence in translucent molecular gas.

7. Comparison with experiments, numerical simulations and chemical models

The present data set discloses small-scale structures of intense velocity-shears that carry the statistical properties of intermittency and, in conjunction with that of HF09, reveals a connexion between parsec-scale and milliparsec scale velocity-shears. The dynamic range of coupled scales in the Polaris Flare is therefore on the order of $\sim 10^3$. Moreover, velocity differences, up to 3.5 km s^{-1} , close to the rms velocity dispersion of the CNM turbulence measured on 10-pc scales (or more) (Miville-Deschênes et al. 2003; Haud & Kalberla 2007), are found in the PdBI field over $\sim 10 \text{ mpc}$, without any detected density enhancement nor shock signature. We argue that the SEE(D)S are the CO-rich parts of straining sheets in a gas undetected in $^{12}\text{CO}(1-0)$, likely the CNM, and that the fast CO enrichment is driven by enhanced turbulent dissipation in the intense velocity-shears. We show below that these findings may be understood in the light of recent

numerical simulations of incompressible and compressible turbulence, and the TDR chemical model of Godard et al. (2009).

The fact that the most dissipative structures appear to be layers of intense strain-rate is consistent with recent results of numerical simulations of incompressible turbulence at high Reynolds number (Moisy & Jiménez 2004) and laboratory experiments (Ganapathisubramani et al. 2008). These regions are not randomly distributed and form inertial-range clusters (Moisy & Jiménez 2004) or develop at the boundaries regions of high level of vorticity (i.e. vortex tubes) (Ganapathisubramani et al. 2008). Coupling between small-scale statistics of the velocity field and the properties of the large-scale flows is also clearly probed in the high- Re numerical simulations of Mininni et al. (2006): correlations are observed between large-scale shear and small-scale intermittency.

In compressible turbulence, the fact that the most dissipative structures are shear-layers is not expected. Yet, in their hydrodynamical simulations of mildly compressible turbulence, Porter et al. (2002) show that the compressible component of the velocity field is weaker than its solenoidal counterpart by a factor ~ 3 , independent of the nature of the driving process (compressible or solenoidal) and Vestuto et al. (2003) find that the energy fraction in the solenoidal modes is dominant and increases with the magnetic field intensity in compressible magneto-hydrodynamical (MHD) turbulence. These numerical experiments are still far from approaching the ISM conditions but they suggest that turbulent dissipation may occur primarily in solenoidal modes, i.e. without direct gas compression, and that the properties of the small scales are coupled to the large-scales.

In the TDR models of Godard et al. (2009), the chemical enrichment of the CNM is driven by high gas temperatures and enhanced ion-neutral drift, without density enhancement. The temperature increase is due to viscous dissipation in the layers of largest velocity-shears at the boundaries of coherent vortices⁴. The large ion-neutral drift occurs in the layers of largest rotational velocity in which ions and magnetic fields decouple from neutrals. These two dissipative processes trigger endothermic chemical reactions, blocked at the low temperature of the CNM. Enrichments consistent with observations are obtained for turbulent rates-of-strain $a = 10^{-11} \text{ s}^{-1}$ induced by large scale turbulence and for moderately dense gas ($n_{\text{H}} < 200 \text{ cm}^{-3}$) characteristic of the CNM. There is no direct determination of the rates-of-strain generated by turbulence in the CNM. We note however that the largest observed velocity-shear (Table 3) corresponds, if the projected quantities provide reasonable estimates, to a comparable rate-of-strain. The range of observed CO column densities from $N(\text{CO}) = 10^{14}$ to $1.6 \times 10^{15} \text{ cm}^{-2}$ can be reproduced by intense velocity-shears occurring in gas of density 100 to 200 cm^{-3} . In this framework, the energy source tapped to enrich the medium in molecules is the supersonic turbulence of the CNM.

The association between the large observed velocity-shears and local enhanced dissipation rate is therefore supported not only by the earlier works presented in the Introduction but also by a quantitative agreement between the TDR chemical models and the present observational results. We cannot rule out however a contribution of low-velocity C-shocks to the turbulent dissipation. If they propagate in the CNM, they are not visible in the CO lines. Such shocks are not yet reliably modelled (Hily-Blant et al., in preparation).

⁴ The “sinews of turbulence” put forward by Moffatt et al. (1994) that link large-scale strain and small-scale vorticity.

8. Conclusions and perspectives

IRAM-PdBI observations of a mosaic of 13 fields in the turbulent environment of a low-mass dense core have disclosed small and weak $^{12}\text{CO}(1-0)$ structures in translucent molecular gas. They are straight and elongated structures but they are not filaments because, once merged with short-spacings data, the PdBI-structures appear as the sharp edges of larger-scale structures. Their thickness is as small as $\approx 3 \text{ mpc}$ (600 AU), and their length, up to 70 mpc, is only limited by the size of the mosaic. Their CO column density is a well determined quantity for the excitation conditions found at larger scale and is in the range $N(\text{CO}) = 10^{14}$ to 10^{15} cm^{-2} . Their H_2 density, estimated in several ways, including the continuum emission of the brightest structure, does not exceed a few 10^3 cm^{-3} . Their well-distributed orientations can be followed in the larger-scale environment of the field. Six of them form three pairs of quasi-parallel structures, physically related. The velocity-shears estimated for the three pairs include the largest ever measured in non-star-forming clouds (up to $780 \text{ km s}^{-1} \text{ pc}^{-1}$).

The PdBI-structures are therefore not isolated and are the edges of so-called SEE(D)S for sharp-edged extended (double) structures. We show that the SEE(D)S are thin layers of CO-rich gas and that their sharp edges pinpoint a small-scale dynamical process, at the origin of the CO contrast detected by the PdBI. We propose that the SEE(D)S are the outcomes of the chemical enrichment driven by intense dissipation occurring in large velocity-shears and that they are CO-rich layers swept along by the straining field of CNM turbulence.

The present work is the first detection of mpc-scale intense velocity-shears belonging to a parsec-scale shear. The large departure from average of the kinematic properties of these structures, confirms that they are a manifestation of the small-scale intermittency of turbulence in this high latitude field, a property already established on statistical grounds (HF09). The values of the velocity-shears (or rate-of-strain) provide a quantitative constraint on the dissipation rate that can be compared to chemical models. The link between the turbulent dissipation in the diffuse gas and the dense core observed in the vicinity of the PdBI mosaic (Fig. 1) still remains to be established.

Last, we would like to stress that sub-structure still exists in these mpc-scale structures of the diffuse ISM and that the next generation of interferometers (e.g. ALMA) should be able to observe gas at the dissipation scale of turbulence (that is still unknown) or at least observe the effects on the ISM (temperature, excitation, molecular abundances) of the huge release of energy expected to occur there.

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Appendix A: Noise level in the mosaic

Mosaic noise is inhomogeneous due to primary beam correction. This is shown in Fig. A.1. The 13-field mosaic produces a large area with uniform noise level. Only at the edge of the mosaic does it increase sharply due to the primary beam correction (the contour shown are at a 2–4 sigma level, 1 sigma being measured at the map center on a channel devoided of signal).

Fig. A.1. Map of the noise level in K km s^{-1} over the 13-field mosaic.

Appendix B: The size-linewidth scaling law

Molecular cloud parameters have long been determined as those of three-dimensional structures isolated in the four-dimensional space of the molecular line data sets $T_L(x, y, v_z)$, the line brightness temperature being a function of position in the *pos* (two coordinates x, y), and one spectral dimension, the projected velocity on the *los* direction v_z . In this 4D space, 3D structures are isolated following different methods (Stutzki & Guesten 1990; Williams et al. 1994; Falgarone & Perault 1987; Loren 1989; Falgarone et al. 1992). The size and linewidth of the large number of clouds displayed in Fig. 10 have been obtained by using published values, corrected in several cases to allow the size and linewidth obey the same definitions in all the samples (see Falgarone 1998). The structures are identified in $^{12}\text{CO}(1-0)$ molecular line surveys of the central parts of the Galaxy (stars, Dame et al. 1986; open triangles Solomon et al. 1987) and of the third quadrant (open hexagons, May et al. 1997), in the Rosette (crosses) and Maddalena (open squares) molecular clouds (Williams et al. 1994), in non-star-forming clouds (solid triangles, Falgarone & Perault 1987; solid squares, Falgarone et al. 1992; tripods, Lemme et al. 1995), in ρ Ophiuchus (solid hexagons, Loren 1989) and in a high latitude cloud (starred triangles, Heithausen et al. 1998).

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