THE STRUCTURE OF QUIESCENT CLOUDS

E. FALGARONE
Radioastronomie Millimétrique, Ecole Normale Supérieure,
24 rue Lhomond, 75005 Paris, France

Abstract. Several tracers of the cold interstellar medium in its quiescent phase reveal common unexpected properties: the fractal nature of the emission contour levels, the self-similar brightness distribution, the existence of small unresolved fragments of dense gas in various environments, and a highly turbulent velocity field. In spite of the difficulties met in interpreting these data, they are important bearings in our understanding of the structure, the physics and the chemistry of this medium.

This paper is a review of the observational grounds of our present knowledge of the structure of quiescent gas. Quiescent gas is defined as the component of the cold interstellar medium which it has not yet formed stars at a level large enough to significantly perturb the gas dynamics and chemistry. Quiescent gas is either mostly atomic or mostly molecular, depending on its shielding from the ambient radiation field. Its hydrogen average column density *at the parsec scale* does not exceed a few $10^{21}\,\mathrm{cm}^{-2}$ and its degree of gravitational binding depends on the linear scale considered. It is a general terminology based on the physics of the gas. It clearly includes diffuse, translucent, and high latitude clouds which have been distinguished in the past on observational grounds (see van Dishoeck, this volume).

1. New observations: general trends

With the recent advent of extremely sensitive detectors in the millimetre, submillimetre and infra-red ranges, a new generation of maps characterized by large dynamical ranges even over regions of weak emission, has brought into light hidden properties of the cold interstellar medium. Eventhough their interpretation is not straightforward, it is encouraging to recognize that most tracers of the column density of quiescent gas agree on several general characteristics which are given below. Those tracers are: the IRAS $100\mu m$ emission which traces the warm dust column density in areas far from star forming regions and the line integrated CO and HI emissions which trace the H_2 and HI column density.

(i) A large connectivity of the emission makes the concept of "cloud" more and more elusive. This is spectacularly illustrated by the most recent IRAS $100\mu m$ maps of the sky produced by the Image Processing and Analysis Center at Caltech (Boulanger, private communication). One of them is shown on the front cover of the proceedings of the IAU Symposium 147.

New CO observations of large areas on the sky, down to unprecedented sensitivity limits, reveal that the previously believed isolated clouds are in fact connected by widespread emission at a very low level. Lee et al. (1990) for instance

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note that it is not possible to define cloud boundaries at a level of 1.2K in the spatial velocity maps of the inner Galatic plane, because, at this level, the emission from all clouds in the map merge together. Heithausen and Thaddeus (1990) have extended their survey of the Polaris Flare to the North Galactic Pole and find that the CO emission extends over $\sim 40\,\mathrm{pc}$ at a level $W(CO) = 0.4\,\mathrm{K\,km\,s^{-1}}$. It corresponds, for the standard CO/H_2 conversion factor, to quite a low column density, $N_{H_2} \sim 10^{20}\,\mathrm{cm^{-2}}$. In these new maps, CO peaks clearly exist but are connected in projection by large areas of low intensity emission.

Recent observations of an HI nearby cloud in Ursa Majoris with the Penticton interferometer also reveal long filamentary structures, the morphology of which is rapidly changing with velocity (Joncas, Boulanger and Dewdney, 1992).

(ii) Unresolved structure exists in all the maps (the smallest observed structures in quiescent gas are $\sim 0.01\,\mathrm{pc}$, a limit provided by single dish observations of rotational transitions of CO in the nearest clouds). This structure is usually more visible in channel maps and is found even in the most transparent parts (Falgarone and Pérault 1988; Falgarone, Phillips and Walker 1991; Falgarone, Puget and Pérault 1992). In the Taurus-Auriga-Perseus complex, a region of average H_2 column density $\sim 8 \times 10^{20}\,\mathrm{cm^{-2}}$ was mapped at high angular resolution in the $^{12}CO(J{=}2{-}1)$ and $(J{=}3{-}2)$ transitions. Holes appear between bright regions of all possible sizes. As in all other maps (infra-red and HI), no characteristic scale is visible.

(iii) There is a clear scale invariance of the maps of integrated emission. The maximal variations of $W(CO)$ in a map, for example, scale with the separation over which they are observed. This scale invariance is at the origin of the fractal geometry of the emission contours discussed below.

Contrasting with the agreement shared by the tracers of column density, large variations are found among "spectral" tracers. Illustrations are provided by Boulanger et al. (1990) who found small scale infrared color fluctuations in the IRAS maps of nearby molecular clouds. They cannot be explained by variations in the ambient radiation field because the UV shielding in these clouds is low everywhere. They likely reveal the existence of complex and rapid exchanges of constituents between the gas phase and the dust grain surfaces.

Another puzzle has been raised by a by-product of the deep CCD survey of faint field galaxies of Guhathakurta and Tyson (1990). They find that, in several high latitude clouds, the visible emission is correlated at large scale with the IRAS 100 μm emission although at small scale fluctuations of the ratio $I_B/I_{100\mu m}$ as large as 10 appear over all sizescales. Alike the IRAS color variations described above, these fluctuations are not easily understood in terms of extinction variations because they occur in gas of extremely low column density.

2. Fractal structure

The first point over which, surprisingly, many authors agree is that the complex structure of the maps can be described with the tools of fractal geometry.

Is fractal a structure in which the number of elements necessary to cover it increases as a power law of either the size of the elements (in a fractal of finite size) or the size of the structure (in a growing fractal). The exponent may be an integer. The fractal behaviour appears as soon as this exponent is smaller than the dimension of the embedding space. The essential property of fractals is their scale invariance.

All the attempts to measure the fractal dimension of the emission contour levels of several tracers of quiescent gas have lead to similar values of D_B. The method used is the same. It is an estimate of the area and perimeter of a given contour, which scale as $P \propto A^{D_B/2}$ if the contour is fractal of dimension D_B. Another independent determination of D_B is provided by the scaling of the perimeter with the resolution ϵ at which it is measured, $P \propto \epsilon^{1-D_B}$ (Lovejoy, 1982).

In the Taurus complex, Falgarone, Phillips and Walker (1990) find that the dimension is the same, $D_B \sim 1.4$, not only at three different linear scales but for three different rotational transitions of CO which are sensitive to gas of different densities. This dimension is comparable to that found on IRAS $100\mu m$ emission maps of the Taurus complex (Scalo, 1990), of a high latitude cloud (Bazell and Désert, 1988) and of other nearby clouds (Dickman, Horvarth and Margulis, 1990) as well as for the HI emission in a high velocity cloud (Wakker 1990).

The surprising fact, namely whichever tracer is used the fractal dimension is the same, suggests that lower density molecular gas and even cold atomic gas are distributed on sets which have the same fractal topology as that of denser gas, for instance that seen in ^{12}CO(J=3–2).

This value is indicative of a possible link between the topology of the cold interstellar medium and the role of turbulence in structuring it. Sreenivasan and Méneveau (1986) measure the same fractal dimension for a variety of interfaces in turbulent flows and more specifically for the surfaces of isodissipation of the kinetic energy.

The knowledge of the fractal dimension of a projected quantity, such as the integrated brightness, does not provide the actual spatial distribution of the gas nor the physics underlying this structure, but it may be used as an indicator to be compared with the dimensions found in other systems in Physics, or for other tracers of matter in Astrophysics. We describe below the methods followed to derive gas densities from the complex maps obtained in the CO rotational lines, for example.

3. Density structure

In addressing the issue of the density of (molecular) clouds, one has to distinguish between the average density over a given sizescale and the local density which may be very different from the former.

The average density in molecular clouds is usually derived from an excess above a local background of integrated CO (or isotopes) emission found in space-velocity maps. This excess is then converted into a column density by using either empirical relations between observed line integrated intensities and the H_2 column density or conversion factors (see the pannel discussion, this conference). The last step is the conversion of the column density N_H into an average density over l, $\overline{n}_H(l) = N_H/l$ where l is the projected size of the observed excess.

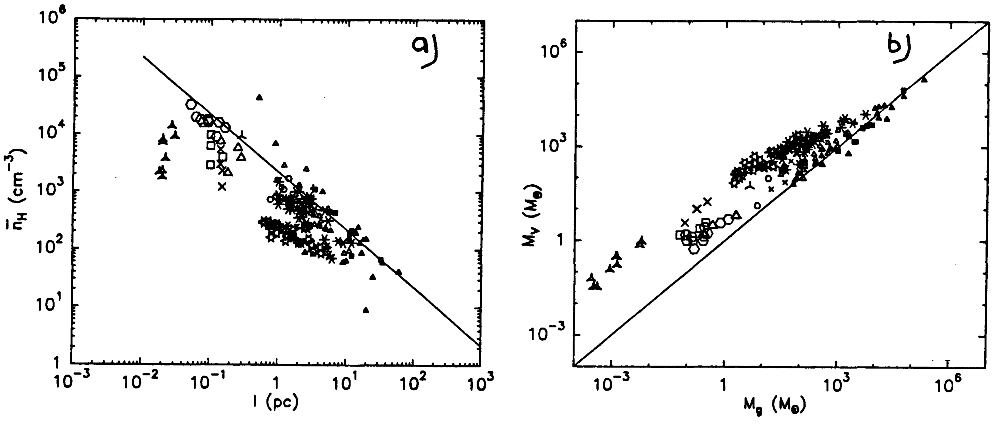

Fig. 1. *(a)* Average hydrogen density versus size in an ensemble of structures from different samples of quiescent gas (large symbols: Falgarone et al. 1992; Herbertz et al. 1991; Carr 1988; small symbols: Falgarone, Pérault and Puget 1985; Falgarone and Pérault 1987). The line $\overline{n}_H \propto l^{-1}$ is that given in Falgarone and Puget (1986) for an ensemble of self-gravitating structures. *(b)* Virial mass versus total gas (hydrogen plus helium) mass for the same structures. The line shows $M_v = M_g$. Note that the sample includes structures up to $M_v \sim 100\ M_g$.

When the works of different groups following comparable methods of analysis over samples of quiescent gas are put together, the net result, illustrated in Fig. 1, is a gross dependence of the maximum average density at a given scale as the inverse of the size down to 0.02 pc with a large spread in each range of size toward low average densities (Falgarone, Puget and Pérault, 1992). As a result, the sample includes structures which span the whole range from far below up to close to virial equilibrium (Fig.1b). The results shown in Fig. 1 have been derived from ^{12}CO, ^{13}CO and C^{18}O data. It is remarkable that no segregation appears among the various density determinations.

The local density in turn is derived from our knowledge of the excitation mechanisms of the rotational levels of molecules. But the derivation is far from straightforward. It implicitly assumes that quiescent gas has general properties, whichever individual cloud it belongs to. It also heavily relies on the scale invariance properties described above and the conclusions are derived from a body of elements rather than from a single set of observations.

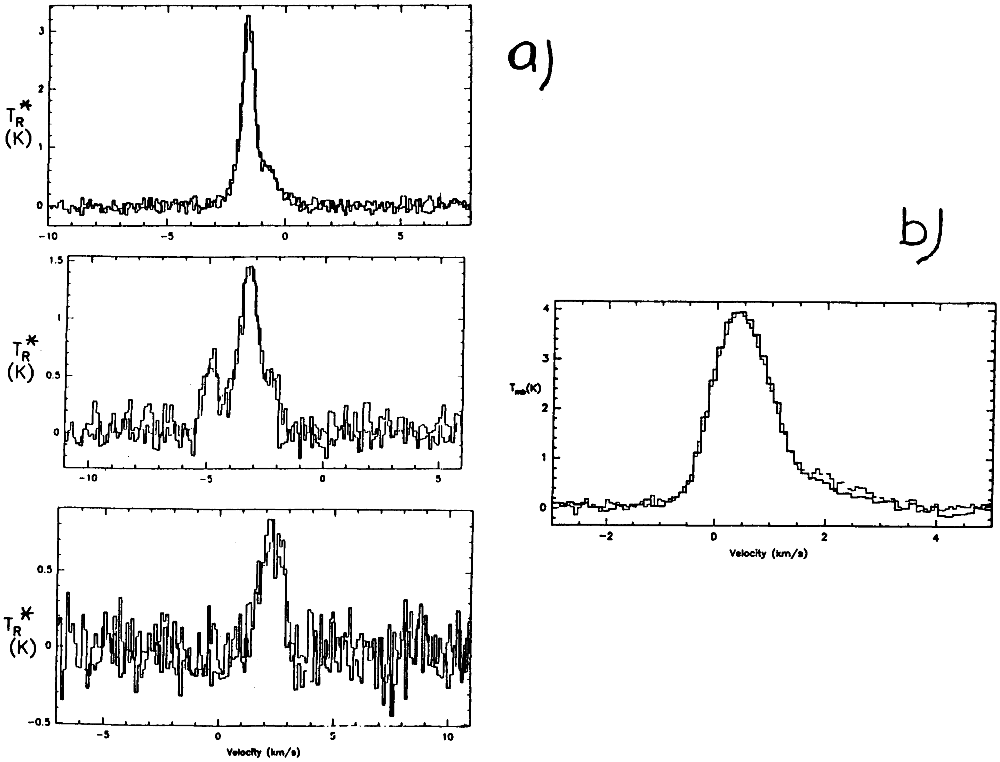

Fig. 2. *(a)* ^{13}CO(J=1–0) (thin line) and (J=2–1) (thick line) spectra of the integrated emission of three different fields in quiescent clouds. Their sizes are respectively 0.07 × 0.07 pc, 0.2 × 0.05 pc and 0.01 × 0.01 pc. The temperature scale is that of the ^{13}CO(J=1–0) line. The 2-1/1-0 line intensity ratios are 0.5, 0.4 and 0.45 respectively. *(b)* Same with the ^{12}CO lines over a different field (size 0.2 pc × 0.1 pc). The line 2-1/1-0 line intensity ratio is 0.75 (main beam temperature).

The major element is the spectacular similarity of the entire J=1-0 and 2-1 profiles in ^{13}CO (Fig. 2a) and ^{12}CO (Fig.2b). It means that the line temperature ratio is uniform over a large range of $N(CO)/\Delta v$ and/or line intensities. Another element is the uniformity of the ^{12}CO(J=3–2) to (J=2–1) line integrated intensity ratio over one order of magnitude of line intensity (Falgarone et al. 1991). These results basically suggest that photon trapping does not play a role in the line excitation. For ^{13}CO, several possibilities exist, namely subthermally excited transitions and warm gas, or thermal excitation in colder gas. But for ^{12}CO, which is optically thick, thermalization is clearly inferred. According to existing excitation models, the local density is therefore of the order of 10^4 cm^{-3} (or even larger) but the exact value is model dependent. The apparent disagreement between the gas density derived by this method and that derived from line absorption profiles in the UV and visible (see van Dishoeck, this volume) is uncomfortable and has to be understood.

It may be argued that the kinetic temperature is not well known. However, an indirect argument (again) favors low kinetic temperatures for the CO emitting regions. The maxima of CO antenna temperature are always low in quiescent regions. Histograms of peak antenna temperatures of several maps show clear maxima between 7K and 9K in the ^{12}CO(J=1–0) line and between 3K and 5K in the ^{12}CO(J=2–1) line (Clemens and Barvainis, 1988). These values suggest kinetic temperatures of the order of 10K or less, if CO emission is thermalized although higher T_k are expected in the least shielded regions.

These results favor a picture in which the CO emission arises in an ensemble of tiny, dense and cold structures, distributed on a fractal set immersed in a lower density and warmer component. The ultimate scale has to be small, $\sim 1000 AU$, because of the observed smoothness of the line profiles (Tauber, Goldsmith and Dickman, 1991; Falgarone et al. 1992).

It is even possible that such tiny dense structures exist in atomic gas. Very Long Baseline Interferometry (VLBI) measurements of HI absorption against several extragalactic sources (Diamond et al. 1989) reveal line opacity variations over angular scales ~ 0.05" possibly originating in dense structures of atomic hydrogen $n_{HI} \sim 10^4 - 10^5\,\mathrm{cm}^{-3}$ smaller than $\sim 25\ AU$. In the summary of their review on the HI emission, Dickey and Lockman (1991) note that "... aperture synthesis observations do show some variations in 21cm opacity on all angular scales".

4. Velocity structure

Quiescent gas is highly turbulent and the observed internal motions have several well-defined properties. The first moments of the velocity distribution scale as $\delta v \propto l^{\alpha}$ with $\alpha \sim 0.4$ (Falgarone et al. 1992), a scaling law similar to that found by Larson (1981) among molecular clouds of all kinds. This scaling is not governed only by gravity since it is found in a large sample of mostly unbound entities, of sizes ranging from 0.05 pc to 50 pc. It is very likely governed by MHD turbulence (Myers and Goodman, 1988a and b). The second characteristic of the velocity field, as provided by the lineprofiles, is the existence of high velocity wings which are not due to stellar outflows. It has been proposed that these wings are due to cloud evaporation (Magnani et al. 1988) to cloud collisions (Keto and lattanzio 1989) or Alfvén waves (Elmegreen 1990). But the scale invariance of the linewings and the fact that the gas which emits in the wings is as dense and cold as that which emits in the cores suggest that the CO line profiles trace the zones of intermittency of the turbulent velocity field (Falgarone and Phillips 1990). They are zones of ephemeral enhanced vorticity and shear which are also those in which the dissipation of the turbulent kinetic energy is concentrated. Intermittency is observed in laboratory flows (Anselmet et al. 1984, in atmospheric clouds (van Atta and Park 1971) and in numerical simulations (Vincent and Meneguzzi 1991). It is characterized by non-Gaussian distributions of the velocity derivatives and increments.

Important consequences can be drawn. The limit between macroscopic and microscopic processes tends to disappear in these regions if one considers that the dissipation scale is only a few times larger than the mean free path for a neutral neutral collision at densities between $10^2\,\mathrm{cm}^{-3}$ and $10^3\,\mathrm{cm}^{-3}$. Also the dissipation zones have been estimated to be very hot. The kinetic temperature depends on their volume filling factor. One finds $T_k \sim 100K - 10^3K$ for $f_v \sim 10^{-3}$ for a low and high ionization degree respectively. This locally high kinetic temperatures do increase the rate of some chemical reactions, in particular radiative associations (Lignières and Falgarone 1992).

5. Concluding remarks

Quiescent clouds have a scale invariant structure with fractal edges of dimension $D_B \sim 1.4 - 1.5$ independent of the tracer used (HI, CO, or $100\,\mu$m) over decades of linear scales (< 0.1 pc to 50 pc). Their structure is very likely the result of MHD turbulence.

CO emitting gas in these clouds is cold, concentrated in tiny units $< 1000AU$. The local density is high $\sim 10^4\,\mathrm{cm}^{-3}$ or even larger, the actual value depending on the collisional excitation rates.

The gas is turbulent and exhibits the signatures of intermittency, in particular the non-Gaussian distribution of the velocity increments. Intermittency might be at the origin of local and transient zones of very high kinetic temperature.

A long list of open questions should follow but the page number limitation has already been overstepped. We anticipate that our understanding of the complex structure of quiescent gas might help elucidating the most flagrant mysteries of chemistry, like the formation of CH^+.

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QUESTIONS AND ANSWERS

J.C.Pecker: You admit that turbulence (the Kolmogorov-spectrum, I presume) governs the fractal behavior of density distribution and "edge" struture. But in some cases, the Kolmogorov spectrum is known to be valid only in a certain scale interval of size (I am refering to Muller and Roudier study of the solar turbulent field). So my question: don't you think that, at unresolved scales, the fractal coefficient D might perhaps change its value (from about 2 to ...less, or to about 3!)? And, if so, could not models admit a possible range of variation of D between the resolved and the unresolved structures?

E.Falgarone: Yes, but there is not even agreement among theorists on the possible different links between the fractal dimension of turbulent interfaces (and dissipation zones) and the slope of the velocity-size power law correlation in laboratory incompressible turbulence. Turbulence in interstellar clouds is still much more complex because of the presence of magnetic field and we are far from being able to model the entire hierarchy.

A.Leger: Can you form CH^+ in your $T = 10^2 - 10^3\,K$ regions?

E.Falgarone: On energetical grounds only, CH^+ formation is therefore possible there. But detailed computations are needed which would include all the time and density dependences, very similar to what has been done in shocks.