STRUCTURE OF MOLECULAR CLOUDS AND TURBULENCE

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1. Introduction

Millimeter wave spectroscopy first revealed the existence, within molecular clouds, of the most opaque cores in which stars form and since then has provided most sophisticated probes of their physical properties. One of them is due to the heterodyne detection itself which allows unmatched spectral resolution in the observations, close to the thermal velocities of molecules at low temperature. Gas motions in molecular clouds are supersonic because the Doppler line broadening is much larger than what would be expected from thermal motions at the low temperatures deduced from line excitation analysis. In 1974, Zuckerman & Evans proposed that these motions were turbulent.

Twenty years later, the nature of the observed supersonic motions is not fully understood. Supersonic turbulence has been discarded for a while because of its large anticipated dissipation rate in radiative shocks, with no comparable injection rate from the known sources of kinetic energy in the medium (explosions of supernovae, HII regions expansion, stellar outflows,...). Recent measurements of the intensity of magnetic field in molecular clouds (see Crutcher et al. 1993) have somewhat released this energetic constraint but the issue of the real nature of the disordered gas motions is still open. Whether these motions are random, turbulent or due to magneto–hydro–dynamics waves is an issue of importance because of their different impact on the physics of the clouds. For instance, as was first proposed by Bonazzola et al. (1987) and further developed in Bonazzola et al. (1992), turbulence with a Kolmogorov spectrum (*i.e.* more power in the large scale motions) is able to stabilize clouds against gravitational instability. This paper reviews the various pros and cons of the turbulent nature of the clouds velocity field and discusses the possible observational signatures of the existence of turbulence.

2. Possible Signposts of Turbulence

2.1. CHARACTERISTICS SHARED WITH INCOMPRESSIBLE TURBULENCE

The gas motions in interstellar clouds are suprathermal, disordered and exhibit features of incompressible turbulence. The Reynolds numbers are extremely large Re $\sim 10^9$ for scale sizes L $\sim$ 1kpc. Much larger scales might even be involved in the cascade since interstellar media in galaxies open up in intergalactic media. Power–law scaling relations have been found in the velocity field of molecular clouds (Fig. 1). Fig. 1a displays the internal non–thermal velocity dispersion versus the size of structures identified in a large variety of data sets. A structure is a connected volume in the space–velocity cube of CO or ^{13}CO emission. The physical meaning of such entities is not yet clear. It involves the complexity of radiative transfer of line photons and the non–linear formation and destruction laws of molecules like CO. In Fig. 1b, the size–linewidth relation is derived from azimuthally averaged structure functions of the velocity field (Miesch & Bally, 1994).

The data points of Fig. 1a reveal a large scatter, particularly at small scale. As an ensemble, they are close to a law $\Delta v \propto l^h$ with $h \sim 1/3$ over an impressive range of sizescales. Entities in virial balance between self–gravity and kinetic energy for which the confining pressure is negligible ($h \sim 1/2$) coexist with structures for which the flatter exponent of the size–linewidth scaling law ($h \sim 1/3$) is reminiscent of the Kolmogorov cascade in incompressible turbulence, as was first proposed by Larson (1981). A comparable dispersion in the slopes of this power–law (between 1/2 and 1/3) is visible in Fig. 1b although the method followed by Miesch & Bally (1994) is different. These authors discuss the possible origins of the different slopes and find they agree with theoretical predictions for the velocity power spectrum when compressibility and magnetic field are taken into account.

Another signpost of turbulence is the fractal dimension of the cloud brightness contours (Scalo, 1990; Falgarone, Phillips & Walker 1991; Zimmermann & Stutzki 1992). This property has been brought together with the multifractal geometry of the dissipation field in laboratory turbulence (see the review of Sreenivasan (1991) and references therein) and it was proposed that the cold cloud population in the interstellar medium traces the regions of enhanced dissipation rate of kinetic energy in a turbulent interstellar medium (Falgarone, Phillips & Walker 1991). One should mention, however, that several other interpretations of the cloud fractal geometry have been proposed, such as collisional fragmentation (Nozakura 1990),

Figure 1. Non–thermal velocity dispersion versus size in an ensemble of molecular clouds. In *(a)*, the velocity dispersion is derived from the extent in velocity space of structures isolated by the level of their line emission in the space–velocity data cubes. The references and corresponding symbols are given in Falgarone, Puget & Pérault (1992). The slope (1/3) predicted by Kolmogorov (1941) for incompressible turbulence is shown. The parallelogram encompasses a large number of data points which correspond to self–gravitating entities. In *(b)*, the power–laws are derived from the structure function of the velocity field built on large data sets (Miesch & Bally 1994).

gravitational clustering and virial balance (Pfenniger & Combes 1994).

No characteristic scale has yet been determined. Unresolved structure is still present in the highest resolution maps of non–starforming clouds and several recent observations bring support to the fact that the threshold of the self–similar hierarchy is indeed very small (down to a few 10 AU) in many kinds of cold clouds. The existence of structures even smaller than 10AU and denser than $n_{\mathrm{H}_2} \sim 10^6\,\mathrm{cm}^{-3}$ has been inferred from secular changes in the formaldehyde absorption line profile toward two extragalactic sources whose lines of sight cross ordinary regions of nearby molecular clouds (Marscher, Moore & Bania 1993; Moore & Marscher 1995). Last, early searches for a finite correlation length in the velocity field of molecular clouds have been unsuccessful (see the reviews of Dickman, 1985, and Scalo, 1987). More recent searches have been similarly inconclusive (Pérault, Falgarone & Puget 1986; Kleiner & Dickman 1987; Kitamura et al. 1993). Further specific signatures of turbulence have been searched for in the shapes of line profiles. They are described below.

2.2. THE SHAPES OF THE LINE PROFILES

The shapes of line profiles, when observed with high spectral resolution, have long been thought of as powerful probes of the nature of the velocity field in clouds although the discussion of the various regimes relevant to the line formation mechanism in terms of systematic to turbulent velocities ratio in the region of line formation has proved quite intricate (Leung, 1978). In 1976, Baker showed that most of the paradoxical behaviours of the CO line shapes and line ratios between isotopic species could be understood if lines form in a macroturbulent medium. New developments along different but complementary lines of thought have brought some clarity in this complex issue. CO line profiles have been computed in random velocity fields with one correlation length (Albrecht & Kegel, 1987; Kegel, Piehler & Albrecht, 1993) which quantitatively illustrates the major role played by the value of a correlation length compared to the photon mean free path.

Three-dimensional numerical simulations of unforced compressible turbulence with a resolution of 512^3 grid points (Porter, Pouquet & Woodward 1994) have been used to synthesize line profiles at different epochs of the simulation, *(i)* when strong shocks have just formed, *(ii)* once shock interactions have generated vorticity, thus transferring most of the kinetic energy to non–compressible modes and *(iii)* in the phase of self–similar decay (Falgarone et al. 1994). In the two latest phases, the synthesized profiles are statistically very similar to observed line profiles, with almost Gaussian profiles coexisting with double–peaked and asymmetric profiles.

The same diversity and similar lineshapes, however, have been found by Dubinski, Narayan & Phillips (1995) who computed line profiles from a random Gaussian velocity field with a Kolmogorov–type power spectrum, under the same approximations as above. The only difference between the profiles synthesized in a random velocity field with Kolmogorov spectrum and those synthesized in a turbulent flow lies in the existence of the weakest and broadest linewings, which trace the presence of local structures of high vorticity, as explained in Falgarone et al. (1994). She, Jackson & Orszag (1990) have shown that structures also exist in a random Gaussian velocity field, in particular vorticity filaments are present. In a turbulent field, though, the intensity of these structures is much larger than in a random velocity field, as illustrated in Figure 2. These intense (coherent) structures are thought to be responsible for the property of intermittency of turbulence, at the origin of the non–Gaussian probability distributions of velocity increments, derivatives and vorticity (Vincent & Meneguzzi 1991; Porter, Pouquet & Woodward 1994). The broadest and weakest linewings in molecular clouds possibly trace the rarest (and most intense) peaks of the vorticity distribution as was proposed in Falgarone & Phillips (1990). There is not a sharp cut–off between the non–Gaussian features due to the Kolmogorov power spectrum itself and those due to intermittency. In a turbulent velocity field, the local enhancements of vorticity, for instance, are just more prominent and more coherent than in a random velocity field. It is this property of turbulence which may imprint very specific signatures on the evolution of interstellar clouds because the regions of enhanced vorticity in turbulent flows are closely associated with those of the largest dissipation rate of kinetic energy. The two subsets of space where these quantities are concentrated are highly structured and intermittent (Brachet 1990; Vincent & Meneguzzi 1991) and the viscous dissipation of turbulence, which eventually heats the gas, does so at a very uneven rate in space and in time.

3. The Intermittent Dissipation of Turbulent Kinetic Energy

3.1. THE GAS TEMPERATURE DISTRIBUTION IN ATOMIC CLOUDS

The local dissipation rate of kinetic energy is $\epsilon_D = \eta/2 \sum_{i,j}(\partial_j v_i + \partial_i v_j)^2$ where $\eta = \rho\nu$ is the dynamical viscosity and ρ the gas mass density. This quantity is best provided by experiments on flows at large Reynolds numbers which allow to estimate the probability distributions of the velocity derivatives down to lengthscales very close to the dissipation length, unlike numerical simulations or observations of the interstellar medium. Flow experiments reported in Gagne (1987) provide the probability distribution functions (PDFs) of velocity increments δv over a large range of lags δl, down to only a few dissipation scales. Estimates of the PDFs of the dissipation rates (averaged over various sizes) can be derived from the distribu-

Figure 2. Upper panel: vorticity field in Navier–Stokes simulations of incompressible turbulence. Lower panel: vorticity distribution (same threshold) in a random Gaussian velocity field with same Kolmogorov power spectrum (from She, Jackson & Orszag 1990)

tions of velocity increments. These results have been scaled to interstellar turbulence by Falgarone & Puget (1995) under the assumption that the statistical flow properties in turbulence only depend on the kinetic energy transfer rate $(\delta v)^3/\delta l$ and on the value of the dissipation scale, l_D which, in atomic clouds, is estimated to be $l_D \sim 10$AU. The resulting locally averaged dissipation rates are found to be local heating sources of interstellar (atomic) clouds that exceed all the others (due to UV photons, coupling to dust grains, cosmic rays...) by orders of magnitude. Moreover, the intense vortices at the origin of the dissipation bursts have been observed to have lifetimes one to two orders of magnitude larger than their own anticipated turnover timescale $\sim \delta v/\delta l$ (see for example the experiment of Douady, Couder & Brachet 1991) and their persistence allows thermal balance to be reached. The lifetime of an intermittent structure of thickness $\delta l \sim$60 AU and characteristic velocity $\delta v_l \sim 0.3$ km s^{-1} is therefore estimated to be $\sim 10^4$ to 10^5 yr. This lifetime being larger than the cooling time associated to radiative processes, thermal balance is reached between the heating provided locally by the intermittent large dissipation of kinetic energy and the radiative cooling of the gas. The unexpected result is that gas temperatures locally as large as $T_k = 10^3$ to 10^4K are found to occur with non negligible probabilities (or filling factors) of 10^{-2} to 10^{-3} within atomic clouds where the bulk of the gas is at T_k =50K.

3.2. IMPLICATIONS FOR THE CHEMICAL REACTIONS

Many chemical reactions with activation barriers of several thousand Kelvin and endothermic reactions can therefore be activated in regions of intermittent large dissipation rate. Time–dependent calculations (Falgarone, Pineau des Forêts & Roueff 1995) show that, as expected, the abundances of molecules like OH, H_2O, CH^+, HCO^+, and therefore CO, in these regions can be orders of magnitude larger than in the surrounding colder gas. A fraction as small as 10% of warm gas at $T_k = 10^3$K on a line of sight across an atomic cloud is sufficient to reproduce the observed quantities of CH^+, a fragile molecule, for which no formation mechanism so far could reproduce the large observed abundance. The large abundances of HCO^+ and other molecules recently discovered in absorption in clouds poorly shielded from the ambient UV radiation field (Lucas & Liszt 1993, 1994, 1996) require a very efficient mechanism for the formation of these molecules. A plausible scenario is the above mechanism, locally powered by the intermittent viscous dissipation of turbulence in otherwise mostly atomic clouds.

3.3. LOCAL CHANGES OF THE DISTRIBUTION OF RELATIVE VELOCITIES BETWEEN SMALL DUST PARTICLES

Intermittency of a turbulent velocity field also affects the relative velocity of two nearby small dust particles. Völk et al. (1980) have shown that turbulence increases the relative velocity of large dust particles but does not affect that of the lightest particles which stay closely coupled to the gas motions. Intermittency introduces timescales for the changes in the topology of the velocity field which are short enough to be comparable to (or smaller than) the friction time of the smallest dust particles so that the distribution of their relative velocities is modified in the regions of strong shear or vorticity (Falgarone & Puget 1995). This process may induce local changes in the size distribution of small particles and may explain the IRAS color variations of dust thermal emission of nearby clouds (Boulanger et al. 1990) or the variations in the shapes of the extinction curves across neighbouring similar clouds (Boulanger et al. 1994). An additional possible confirmation that such processes occur even in diffuse clouds is the correlation between the mid–infrared 12μm continuum emission of high latitude clouds and their CH^+ equivalent width (Boulanger 1994).

4. Summary

All the above cannot be taken as a proof that turbulence exists in interstellar clouds but it puts together a set of significant signatures of turbulence. In spite of the complexity of the physics of interstellar clouds, and the many processes which generate non–linear behaviours, it seems that the velocity patterns, the shapes of molecular lines, the line ratio properties, all suggest that a Kolmogorov–type cascade is present with the additional property of intermittency characteristic of turbulence. Unlike what is commonly thought, the fact that interstellar clouds share so many properties with incompressible turbulence is not in contradiction with their compressibility. Recent numerical simulations (Porter et al. 1994) have shown that shock interactions rapidly generate vorticity, increasing the energy in the incompressible modes at the expense of that in compressible modes which builds up a Kolmogorov power spectrum.

The property of intermittency is responsible for the local characteristics of the gas to considerably depart from their average values, as derived for instance from the observations. These large amplitude and non–Gaussian fluctuations induced at small scale in the temperature or the chemical content of the gas may be at the origin of the most profound difficulty met in modelling interstellar clouds and understanding their small–scale evolution. At large scale, however, the gross properties of the cycle of the interstellar medium through its different phases, up to star formation, have been successfully reproduced in numerical simulations which take into account the interplay of self–gravity, turbulence and compressibility of the flows (Vásquez–Semadeni, Passot & Pouquet 1995).

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