The Origin of Molecular Cloud Turbulence and its role on Determining the Star Formation Efficiency

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Abstract. We suggest that molecular cloud (MC) turbulence is a consequence of the very process of MC formation by collisions of larger-scale flows in the diffuse atomic gas, which generate turbulence in the accumulated gas through bending-mode instabilities. Turbulence is thus maintained for as long as the accumulation process lasts (∼several Myr). Assuming that supersonic turbulence in MCs has the double role of preventing global collapse while promoting the formation of smaller-scale structures by turbulent compression (“turbulent fragmentation”), we then note the following properties: a) Turbulent fragmentation necessarily deposits progressively smaller fractions of the total mass in regions of progressively smaller sizes, because the smaller structures are subsets of the larger ones. b) The turbulent spectrum implies that smaller scales have smaller velocity differences. Therefore, below some scale, denoted $l_{eq}$, the turbulent motions become subsonic. This is an energy distribution phenomenon, not a dissipative one. On this basis, we propose that the star formation efficiency (SFE) is determined by the fraction of the total mass that is deposited in clumps with masses larger than $M_J(l_{eq})$, the Jeans mass at scale $l_{eq}$, because subsonic turbulence cannot promote any further subfragmentation. In this scenario, the SFE should be a monotonically increasing function of the sonic and turbulent equality scale, $l_{eq}$. We present preliminary numerical tests supporting this prediction, and thus the suggestion that (one of the) relevant parameter(s) is $l_{eq}$, and compare with previous proposals that the relevant parameter is the energy injection scale.

1. Introduction

Two of the main questions concerning molecular cloud (MC) structure and star formation are a) what is the origin and supply of MC turbulence? and b) what is the origin of the low efficiency of star formation? Indeed, MCs are known to be turbulent, with motions that are supersonic at scales $\gtrsim 0.1$ pc (Zuckerman & Evans 1974; Larson 1981). However, recent numerical simulations (Padoan & Nordlund 1999; Mac Low et al. 1998; Stone, Ostriker & Gammie 1998; Mac
Low 1999; see also Avila-Reese & Vázquez-Semadeni 2001 for the case of the global ISM) have suggested that strong MHD turbulence decays rapidly even in the presence of strong magnetic fields. Thus, it appears that MC turbulence must be continually driven during the entire lifetime of the clouds. The driving mechanism, however, is probably not restricted to the stellar activity internal to the clouds, since clouds devoid of stars exhibit similar turbulent properties as clouds with stars (e.g., McKee 1999 and references therein).

Concerning the star formation efficiency (SFE), it is well known that it is low, on the order of a few percent with respect to the total cloud mass. Traditional explanations for this low efficiency have been, in the case of low-mass, isolated star formation, that the MC cores in which stars form are magnetically supported (i.e., “subcritical”), so that collapse is delayed until the magnetic field diffuses out of the core by ambipolar diffusion (see, e.g., Shu, Adams & Lizano 1987). However, there exist several recent suggestions that all cores are critical or supercritical (e.g., Nakano 1998; Hartmann, Ballesteros-Paredes & Bergin 2001; Bourke et al. 2001; Crutcher, Heiles & Troland 2002). On the other hand, it is known that turbulence can prevent global gravitational collapse of a cloud when the energy injection scale is smaller than the Jeans length (Léorat, Passot & Pouquet 1990; Klessen, Heitsch & Mac Low 2000, hereafter KHM00), while promoting “fragmentation”, i.e., the formation of smaller-scale density substructures that can possibly undergo local collapse (Sasao 1973; Tohline, Bodenheimer & Christodoulou 1987; Elmegreen 1993; Vázquez-Semadeni, Passot & Pouquet 1996; Padoan 1995; Padoan et al. 2001; KHM00). KHM00 have shown that the efficiency in numerical simulations (measured as the fraction of mass in collapsed objects) is large when the energy injection scale is larger than the Jeans length, and low otherwise. However, it is possible, as we suggest in §2 that MC turbulence is part of a cascade coming from larger scales. Thus, the description in terms of an energy injection scale smaller than the MC itself is probably not optimal for real MCs. Also, this shows that the origin of MC turbulence and of the SFE are intimately related.

In the present paper, we propose that MC turbulence originates from the same process that forms the clouds (§2), and sets an upper limit to the SFE through the fraction of the total mass it deposits in regions with sizes such that the turbulent velocity dispersion becomes subsonic (so that no further subfragmentation can occur within them), and masses larger than their Jeans mass (§3).

2. Origin of molecular cloud turbulence

In this section we suggest, without proof, a plausible scenario for the production of MC turbulence as a byproduct of their formation process. It has been proposed that MCs are formed by the convergence of large-scale streams in the diffuse ISM (Elmegreen 1993; Ballesteros-Paredes, Vázquez-Semadeni & Scalo 1999, hereafter BVS99). Although the MCs formed in the global ISM simulations of BVS99 were at the limit of the resolution, rendering it impossible to resolve the internal structure of the resulting clouds, one can infer it from other pieces of evidence. This cloud formation mechanism is analogous to the formation of shock-bounded slabs between convergent flows, a process which is known to be
subject to fragmentation through nonlinear instabilities (Vishniac 1994). This process has been simulated numerically by various groups (Hunter et al. 1986; Klein & Woods 1998; Folini & Walder 1998), showing that it generates fully developed turbulence in the shocked slab. Therefore, one expects turbulence to be maintained for the entire duration of the stream collision that forms the MC. In this scenario, MCs and their internal turbulence are the consequence of a lossy energy cascade in compressible turbulent flows, in which at every scale a fraction of the energy is dissipated directly by shocks and the remainder is passed to smaller-scale structures (Kornreich & Scalo 2000). Also, since the resulting MC is not confined to a closed box, contrary to the case of simulations of isolated clouds, and the compressible turbulence generated produces both excesses and defects in the density field, part of the material of the cloud can be dispersed during the process. Numerical experiments aimed at investigating this process in detail are now underway using adaptive-grid and SPH numerical techniques, and will be reported elsewhere.

3. Turbulent Control of the Star Formation Efficiency

Assuming that turbulence is maintained for the lifetime of the MC as described above, then the spatial redistribution ("turbulent fragmentation") of both mass and the various energies it produces implies that only a fraction of the mass in the turbulent cloud can end up in collapsed structures, assuming that the total turbulent+thermal (collectively referred to as "kinetic") energy is comparable to its self-gravitating energy. In this case, the kinetic energy provides support against global collapse of the whole cloud, while simultaneously it promotes the production of smaller-scale density structures through turbulent compressions, with the process repeating itself at subsequently smaller scales, until a change of regime occurs. A natural scale for a transition regime is the scale at which the turbulent velocity difference becomes equal to the sound speed, denoted $l_{eq}$. Below this scale, the turbulence becomes subsonic, and is incapable of producing further subfragmentation. Moreover, at this scale, thermal energy becomes dominant in the support of the substructures, and thus the Jeans criterion becomes the relevant one for determining whether a given density peak (a "core") can become gravitationally dominated and collapse. Given the statistical distribution of core masses and sizes formed by the turbulence, only a fraction of the structures of size $l_{eq}$ will have masses larger than the Jeans mass at this scale.

Since the turbulent fragmentation deposits ever smaller fractions of the total mass in ever smaller-size structures, the present scenario implies that flows with smaller values of $l_{eq}$ must have smaller fractions of mass available for collapse. This can be tested experimentally by setting up simulations with different ratios of turbulent to thermal energy, so that they have different values of $l_{eq}$. To do this, we use the simulations of non-magnetic isothermal turbulence of KHM00, which include cases with the same total kinetic energy, but forced at different scales, so that $l_{eq}$ is different, and simulations with different amounts of kinetic energy, but similar $l_{eq}$. In fig. 1 we show the turbulent energy spectra of three of

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1Note that $l_{eq}$ is just a characteristic scale for this to occur, there being a distribution of clump sizes at which the equality occurs.
Figure 1. (Left panel:) Turbulent energy spectra for three simulations of isothermal, self-gravitating, compressible, non-magnetic turbulence by KHM00, labeled A1, A3 and B1, all with the same mass. Runs A1 and A3 have the same total kinetic (turbulent+thermal) energy, but different spectral turbulent energy distribution, so that run A3 has more energy at small scales (large wavenumbers $k$). Run B1 has more total kinetic energy than A1 and A3, but its spectrum nearly coincides with that of A3 at small scales, thus having nearly equal values of $l_{eq}$, denoted by the vertical dashed lines. (Right panel:) SFE, measured as the fraction of mass in collapsed cores in the simulation as a function of time (from KHM00). Runs A3 and B1 are seen to have very similar values of the SFE.

4. Conclusions

We have shown numerical evidence that $l_{eq}$ is a relevant parameter in setting an upper limit to the SFE (other processes, such as stellar energy feedback, may contribute as well). However, it is most likely that other parameters are also involved. In particular, as the spectral energy distribution of the turbulence varies, the sizes of the density structures are likely to change as well. Padoan (1995) made an attempt in this direction based on the probability distribution function (PDF) of the density field. However, the PDF contains no information of the mass spatial distribution. What is necessary is the density PDF parame-
terized by region size. This is precisely the kind of information contained in the multifractal spectrum, and which we are in the process of incorporating into the treatment.

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