TURBULENT CONTROL OF THE STAR FORMATION EFFICIENCY

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Abstract
Supersonic turbulence plays a dual role in molecular clouds: On one hand, it contributes to the global support of the clouds, while on the other it promotes the formation of small-scale density fluctuations, identifiable with clumps and cores. Within these, the local Jeans length $L_{J,c}$ is reduced, and collapse ensues if $L_{J,c}$ becomes smaller than the clump size and the magnetic support is insufficient (i.e., the core is “magnetically supercritical”); otherwise, the clumps do not collapse and are expected to re-expand and disperse on a few free-fall times. This case may correspond to a fraction of the observed starless cores. The star formation efficiency (SFE, the fraction of the cloud’s mass that ends up in collapsed objects) is smaller than unity because the mass contained in collapsing clumps is smaller than the total cloud mass. However, in non-magnetic numerical simulations with realistic Mach numbers and turbulence driving scales, the SFE is still larger than observational estimates. The presence of a magnetic field, even if magnetically supercritical, appears to further reduce the SFE, but by reducing the probability of core formation rather than by delaying the collapse of individual cores, as was formerly thought. Precise quantification of these effects as a function of global cloud parameters is still needed.

1. Introduction
The observed efficiency of star formation (SFE, the fraction of a cloud’s mass deposited in stars during its lifetime) is low, on the order of a few percent (e.g., Evans 1991). For over two decades, the accepted explanation (Mouschovias 1976a,b; Shu, Adams & Lizano 1987) to this low observed SFE was that low-mass stars form in so-called “magnetically subcritical” molecular clouds, which, under ideal MHD conditions (perfect flux freezing), would be absolutely supported by magnetic forces against their own self-gravity, regardless of the external pressure. In
practice, however, in dense clumps within the clouds, the ionization fraction drops to sufficiently low values that the process known as “ambipolar diffusion” (AD; Mestel & Spitzer 1956) allows quasi-static contraction of the clumps into denser structures (“cores”), and ultimately collapse. The low SFE then arises from the fact that only the material in the densest regions could proceed to gravitational collapse, and on the AD time scale, which is in general much larger than the free-fall time scale. High-mass stars, on the other hand, were proposed to form from either supercritical clouds assembled by agglomeration of smaller clouds into large complexes (Shu, Adams & Lizano 1987), or by super-Alfvénic shock compression of sub- or nearly critical clouds (Mouschovias 1991).

In this scenario, which we refer to as the “standard model” of star formation, gravitational fragmentation along flux tubes containing many Jeans masses (e.g., Shu et al. 1987; Mouschovias 1991), was considered to be the mechanism responsible for clump formation.

However, molecular clouds are known to be supersonically turbulent (e.g., Zuckerman & Evans 1974; Larson 1981; Blitz 1993), and this is bound to produce large density fluctuations, even if the turbulence is sub-Alfvénic.\(^1\) In this case, the clumps and cores within molecular clouds, as well as the clouds themselves, are likely to be themselves the turbulent density fluctuations within the larger-scale turbulence of their embedding medium (von Weizsäcker 1951; Sasao 1973; Elmegreen 1993; Ballesteros-Paredes, Vázquez-Semadeni & Scalo 1999), being transient, time-dependent, out-of-equilibrium objects in which the kinetic compressive energy of the large-scale turbulent motions is being transformed into the internal, gravitational and perhaps smaller-scale turbulent kinetic energies of the density enhancements. The typical formation time scales of the density fluctuations should be of the order of the rms turbulent crossing time across them.

If clumps and cores within molecular clouds are indeed formed through this rapid, dynamic process, such an origin and out-of-equilibrium nature appear difficult to reconcile with the quasi-magnetostatic nature of the AD contraction proposed to occur in the standard model. Moreover, a number of additional problems with the standard model have been identified (see the review by Mac Low & Klessen 2004), among which a particularly important one is that molecular clouds are generally observed to be magnetically supercritical or nearly critical (e.g., Crutcher 1999, 2003; Bourke et al. 2001), in agreement with expectations.

\(^1\)In fact, numerical simulations suggest that strongly magnetized cases develop larger density contrasts than weakly magnetized ones (e.g., Passot, Vázquez-Semadeni & Pouquet 1995; Ostriker, Gammie & Stone 1999; Ballesteros-Paredes & Mac Low 2002).
from the cloud formation mechanism (Hartmann, Ballesteros-Paredes & Bergin 2001).

In this paper we review how the SFE can be maintained at low levels within the context of what has become known as the “turbulent model” of molecular cloud formation, without having to necessarily resort to quasi-static, AD-mediated slow contraction.

2. Turbulent control of gravitational collapse

In this section we consider the role of turbulence neglecting the magnetic field.

In most early treatments of self-gravitating clouds, turbulence had been considered only as a source of support (e.g., Chandrasekhar 1951; Bonazzola et al. 1987; Lizano & Shu 1989). However, one of the main features of turbulence is that it is a multi-scale process, with most of its energy at large scales. Thus, it is expected to have a dual role in the dynamics of molecular clouds (Vázquez-Semadeni & Passot 1999): over all scales on which turbulence is supersonic, it is the dominant form of support, while simultaneously it induces the formation of small-scale density peaks (“clumps”). If the latter are still supersonic inside, further, smaller-scale peak formation is expected in a hierarchical manner (Vázquez-Semadeni 1994; Passot & Vázquez-Semadeni 1998), until small enough scales are reached that the typical velocity differences across them are subsonic, at which point turbulent energy ceases to be dominant over thermal energy for support, and also further turbulent subfragmentation cannot occur (Padoan 1995; Vázquez-Semadeni, Ballesteros-Paredes & Klessen 2003). These can be identified (Klessen et al. 2005) with “quiescent” (Myers 1983), “coherent” (Goodman et al. 1998) cores. We refer to the scale at which the typical turbulent velocity difference equals the sound speed as the “sonic scale”, denoted $\lambda_s$. It depends on both the slope and the intercept of the turbulent energy spectrum.

For a molecular cloud of mean density $n \sim 10^3$ cm$^{-3}$ and temperature 10 K, the thermal Jeans length is $L_{\text{J}} \sim 0.7$ pc, and so sub-parsec clumps will generally be smaller than the cloud’s global Jeans length $L_{\text{J,g}}$. However, in the clumps, the local Jeans length $L_{\text{J,c}}$ is reduced, and in some cases it may become smaller than the clump’s size, at which point the clump can proceed to collapse. If the clump is internally subsonic, then $L_{\text{J,c}}$ is given by the thermal Jeans length; otherwise, $L_{\text{J,c}}$ should include the turbulent support (Chandrasekhar 1951). Moreover, in the latter case, the clump can still fragment due to the turbulence, with the fragments collapsing earlier than the whole clump (because they have
shorter free-fall times), probably producing a bound cluster. On the other hand, if $L_{J,c}$ never becomes smaller than clump’s size during the compression, then the clump is expected to re-expand after the turbulent compression ends, on times a few times larger than the free-fall time (Vázquez-Semadeni et al. 2005). This is because in the absence of a magnetic field, stable equilibria of self-gravitating isothermal spheres require the presence of an external, confining pressure. In the case of clumps formed as turbulent fluctuations, the external pressure includes the fluctuating turbulent ram pressure, and is therefore time variable, being at a maximum when the clump is being formed, and later returning to the mean value of the ambient thermal pressure.

The formation of collapsing objects is a highly nonlinear and time dependent process, which is most easily investigated numerically. Early studies in two dimensions suggested that gravitational collapse could be almost completely suppressed by turbulence driving if the driving was applied at scales smaller than the global Jeans length (Léorat, Passot & Pouquet 1990). This was later supported by the 3D studies of Klessen, Heitsch & Mac Low (2000), who investigated the evolution of the collapsed mass fraction as a function of the rms Mach number and the driving scale of the turbulence in numerical simulations of isothermal, non-magnetic, self-gravitating driven turbulence. However, for driving scales larger than $L_{J,g}$, Klessen et al. (2000) still found collapsed fractions well below unity, showing that the SFE is reduced even if the driving scale is larger than $L_{J,g}$. This is important because it is likely that the turbulence in molecular clouds is driven from large scales (Ossenkopf & Mac Low 2002), the clouds actually being part of the general turbulent cascade in the ISM (Vázquez-Semadeni et al. 2003). In this case, the driving scale is not a free parameter, and the ability to reduce the SFE even with large-scale driving is essential.

Vázquez-Semadeni et al. (2003) later showed that, for the simulations they considered, all of which had the same number of Jeans lengths in the box ($J$, equal to 4 there), the SFE correlates better with the sonic scale than with either the rms Mach number or the driving scale, substantiating the relevance of the sonic scale. The correlation was empirically fit to a function of the form $\text{SFE} \propto \exp(-\lambda_0/\lambda_s)$, with $\lambda_0 \sim 0.11 \text{ pc}$ in the simulations studied. If the driving scale is kept constant (say, at its largest possible value), then the dependence of the SFE on the sonic scale translates directly into a dependence on the Mach number. Indeed, the data of Klessen et al. (2001) and of Vázquez-Semadeni et al. (2003) show that the SFE in simulations driven at a fixed scale is systematically reduced as the Mach number is increased. For example, in simulations driven at $2L_{J,g}$, efficiencies $\sim 40\%$ were observed for rms
Mach numbers ~ 10 (Vázquez-Semadeni et al. 2003). A theory explaining this functional dependence is lacking. Moreover, the experiments so far remain incomplete, since they have not tested the dependence of the SFE on the Jeans number of the flow J.

In summary, in the non-magnetic case, the numerical experiments show that the SFE can be reduced by turbulence alone, without the need for magnetic fields. However, for realistic rms Mach numbers, the efficiencies observed are still larger than observed if one admits that clouds are likely to be driven at large scales.

3. The role of the magnetic field

The magnetic field may provide the necessary further reduction of the SFE to reach the observed levels, even in supercritical clouds. Early numerical studies showed that global collapse in a magnetic simulation can only be completely suppressed if the box is magnetically subcritical and AD is neglected (Ostriker et al. 1999; Heitsch, Mac Low & Klessen 2001). Supercritical boxes readily collapse, although on time scales up to twice the global free-fall time $\tau_{g}$. Heitsch et al. (2001) and Li et al. (2004) additionally have shown that MHD waves within supercritical clumps are apparently insufficient to prevent their collapse. Heitsch et al. (2001) also investigated the collapsed mass fraction as a function of magnetization in supercritical boxes, but were not able to find any clear trends, because the effect of the magnetic field was obscured by stochastic variations between different realizations of flows with the same global parameters.

Recently, Li & Nakamura (2004) have considered the same issue in two-dimensional, decaying (rather than driven) simulations, in both sub- and supercritical regimes, including a prescription for AD. They found that stronger magnetic fields delay the initial formation of collapsed objects, although all their simulations at a fixed Mach number achieved comparable final collapsed mass fractions at long times. They also concluded that higher levels of initial turbulence speed up the collapse in subcritical clouds by producing high-density clumps in which the AD time scale is short, and thus avoiding the problem that AD by itself gives collapse times that are too long compared to observational evidence (e.g., Jijina, Myers & Adams 1999; Lee & Myers 1999; Hartmann 2003).

The above studies have focused on the global collapsed mass fraction in simulations, but further insight can be obtained by focusing on the evolution of individual clumps. Vázquez-Semadeni et al. (2005) have investigated the evolution of individual clumps in three-dimensional,
driven MHD simulations neglecting AD. These showed that the typical times for clumps to go from mean densities $\sim 10^4 \text{ cm}^{-3}$ (the level of the densest fluctuations produced by the turbulence in their Mach-10 simulations) to full collapse differ by less than a factor of 2 between supercritical and non-magnetic simulations, being $\lesssim 2\tau_{l,c} \sim 1 \text{ Myr}$ in the former, and $\sim 1\tau_{l,c} \sim 0.5 \text{ Myr}$ in the latter, where $\tau_{l,c} \equiv L_{l,c}/c$ is the local free-fall time in the clumps, and $c$ is the isothermal sound speed. Furthermore, these authors showed that in subcritical simulations without AD, in which collapse cannot occur, the clumps only reached mean densities $\sim 10-20 \times 10^4 \text{ cm}^{-3}$, to then rapidly become dispersed again in times $\sim 1 \text{ Myr}$. An estimate of the AD time scale $\tau_{AD}$ in one such clump taking into account its closeness to the critical mass-to-flux ratio (Ciolek & Basu 2001) gave $\tau_{AD} \gtrsim 1.3 \text{ Myr}$, suggesting that in the presence of AD the clump might possibly increase its mass-to-flux ratio and proceed to collapse by the effect of AD, although on time scales not significantly longer than the dynamical ones observed in the supercritical and non-magnetic simulations. If AD acts on significantly longer time scales, then it cannot bind the clumps before they are dispersed by the turbulence.

Vázquez-Semadeni et al. (2005) also noticed that the appearance of the first collapsing cores in the supercritical simulations was delayed with respect to the non-magnetic simulation, and that fewer cores formed in the magnetic cases than in the non-magnetic one. These findings are consistent with previous results that the presence of the magnetic field delays the collapse (Ostriker et al. 1999; Heitsch et al. 2001), but suggests that the delay at the global scale occurs by reducing the probability of forming collapsing cores, rather than by delaying the collapse of individual clumps. This may be the consequence of the magnetic field reducing the effective dimensionality of turbulent compressions, which become nearly one-dimensional in the limit of very strong fields, in which case the compressions cannot produce collapsing objects (e.g., Shu, Adams & Lizano 1987; Vázquez-Semadeni, Passot & Pouquet 1996).

4. Conclusions

The results summarized here show that the SFE in supersonically turbulent molecular clouds is naturally reduced because the turbulence opposes global cloud collapse while inducing the formation of local density peaks that contain small fractions of the total mass, and which may collapse if they become locally gravitationally unstable. However, not all density peaks (“clumps”) manage to do so, and a number of them are expected to instead re-expand and merge with their environment. This
mechanism operates even in the absence of magnetic fields, although for realistic parameters of the turbulence, the efficiencies in numerical simulations are higher than observed. Including the magnetic field further reduces the efficiency of collapse, even in supercritical cases, but apparently not by delaying the formation and collapse of individual clumps, which occurs on comparable time scales in both the magnetic and non-magnetic cases, but by reducing the probability of collapsing-core formation by the turbulence. Further work is now needed to quantify the SFE and the fraction of collapsing versus non-collapsing peaks as a function of the global parameters, and to eventually produce a collective theory that describes the process in a statistical fashion.

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References

Ballesteros-Paredes, J., Vázquez-Semadeni, E., & Scalo, J. 1999a, ApJ, 515, 286
Ballesteros-Paredes, J. & Mac Low, M. 2002, ApJ, 570, 734
Blitz, L., 1993, in “Protostars and Planets III”, eds. E. H. Levy and J. I. Lunine (Tucson: Univ. of Arizona Press), 125
Bonazzola, S., Heyvaerts, J., Falgarone, E., Pérault, M. & Puget, J. L., A&A 172, 293
Bourke, T. L., Myers, P. C., Robinson, G., Hyland, A. R. 2001, ApJ 554, 916
Ciolek, G. E. & Basu, S. 2001, ApJ 547, 272
Chandrasekhar, S. 1951, Proc. R. Soc. London A, 210, 26
Crutcher, R. M. 1999, ApJ 520, 706
Crutcher, R. 2004, in “Magnetic Fields and Star Formation: Theory versus Observations”, eds. Ana I. Gomez de Castro et al, (Dordrecht: Kluwer Academic Press), in press
Elmegreen, B. G. 1993, ApJL, 419, 29
Evans, N. J., II 1991, in Frontiers of Stellar Evolution, ed. D. L. Lambert (San Francisco: ASP), 45
Goodman, A. A., Barranco, J. A., Wilner, D. J., & Heyer, M. H. 1998, ApJ 504, 223
Hartmann, L. 2003, ApJ 585, 398
Hartmann, L., Ballesteros-Paredes, J., & Bergin, E. A. 2001, ApJ, 562, 852
Heitsch, F., Mac Low, M. M., & Klessen, R. S. 2001, ApJ, 547, 280
Jijina, J., Myers, P. C., & Adams, F. C. 1999, ApJS 125, 161
Klessen, R. S., Heitsch, F., & MacLow, M. M. 2000, ApJ, 535, 887
Klessen, R. S., Ballesteros-Paredes, J., Vázquez-Semadeni, E. C. & Durán, C. 2004, ApJ, submitted (astro-ph/0306055)
Larson, R. B. 1981, MNRAS, 194, 809
Lee, C. W. & Myers, P. C. 1999, ApJS 123, 233
Léorat, J., Passot, T. & Pouquet, A. 1990, MNRAS 243, 293
Li, Z.-Y. & Nakamura, F. 2004, ApJL, in press (astro-ph/0405615)
Lizano, S., & Shu, F. H. 1989, ApJ, 342, 834
Mac Low, M.-M. & Klessen, R. S. 2004, Rev. Mod. Phys. 76, 125
Mestel, L., Spitzer, L., Jr. 1956, MNRAS 116, 503
Mouschovias, T. C. 1976a, ApJ 207, 141
Mouschovias, T. C. 1976b, ApJ 206, 753
Mouschovias, T. C. 1991, in The Physics of Star Formation and Early Stellar Evolution, eds. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 449
Myers, P. C. 1983, ApJ 270, 105
Ossenkopf, V. & Mac Low, M.-M. 2002, A&A 390, 307
Ostriker, E. C., Gammie, C. F. & Stone, J. M. 1999, ApJ 513, 259
Padoan, P. 1995, MNRAS, 277, 377
Passot, T., Vázquez-Semadeni, E. & Pouquet, A. 1995, ApJ 455, 536
Passot, T. & Vázquez-Semadeni, E. 1998, Phys. Rev. E 58, 4501
Sasao, T. 1973, PASJ 25, 1
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARAA, 25, 23
Vázquez-Semadeni, E. 1994, ApJ 423, 681
Vázquez-Semadeni, E., Passot, T. & Pouquet, A. 1996, ApJ 473, 881
Vázquez-Semadeni, E. & Passot, T. 1999, in Interstellar Turbulence, ed. J. Franco & A. Carramiñana (Cambridge: Univ. Press), 223
Vázquez-Semadeni, E., Ballesteros-Paredes, J. & Klessen, R. S. 2003, ApJL 585, 131
Vázquez-Semadeni, E., Kim, J., Shadmehri, M. & Ballesteros-Paredes, J. 2005, ApJ, in press (astro-ph/0409247)
von Weizsäcker, C.F. 1951, ApJ 114, 165
Zuckerman, B. & Evans, N. J. II 1974, ApJL 192, 149
Zuckerman, B. & Palmer, P. 1974, ARAA 12, 279