

# Molecular cloud turbulence and the star formation efficiency: enlarging the scope

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**Abstract.** We summarize recent numerical results on the control of the star formation efficiency (SFE), addressing the effects of turbulence and the magnetic field strength. In closed-box numerical simulations, the effect of the turbulent Mach number  $\mathcal{M}_s$  depends on whether the turbulence is driven or decaying: In driven regimes, increasing  $\mathcal{M}_s$  with all other parameters fixed decreases the SFE, while in decaying regimes the converse is true. The efficiencies in non-magnetic cases for realistic Mach numbers  $\mathcal{M}_s \sim 10$  are somewhat too high compared to observed values. Including the magnetic field can bring the SFE down to levels consistent with observations, but the intensity of the magnetic field necessary to accomplish this depends again on whether the turbulence is driven or decaying. In this kind of simulations, a lifetime of the molecular cloud (MC) needs to be assumed, being typically a few free-fall times. Further progress requires determining the true nature of the turbulence driving and the lifetimes of the clouds. Simulations of MC formation by large-scale compressions in the warm neutral medium (WNM) show that the generation of the clouds' initial turbulence is built into the accumulation process that forms them, and that the turbulence is driven for as long as accumulation process lasts, producing realistic velocity dispersions and also thermal pressures in excess of the mean WNM value. In simulations including self-gravity, but neglecting the magnetic field and stellar energy feedback, the clouds never reach an equilibrium state, but rather evolve secularly, increasing their mass and gravitational energy until they engage in generalized gravitational collapse. However, local collapse events begin midway through this process, and produce enough stellar objects to disperse the cloud or at least halt its collapse before the latter is completed. Simulations of this kind including the missing physical ingredients should contribute to a final resolution of the MC lifetime and the origin of the low SFE problems.

**Keywords.** ISM: Clouds, stars:formation, turbulence, magnetic fields.

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## 1. Introduction

Molecular clouds (MCs) are the densest regions in the interstellar medium (ISM) and also the site of all present-day star formation in the Galaxy. They are known to have masses much larger than their thermal Jeans mass, a fact that led Goldreich & Kwan (1974) to propose that the clouds should be in a state of generalized gravitational collapse. However, Zuckerman & Palmer (1974) readily noted that this would imply that the MCs should be forming stars at very high rates ( $\sim 30M_{\text{sun}} \text{ yr}^{-1}$ ) if all of their mass were to be transformed into stars in roughly one free-fall time  $\tau_{\text{ff}}$ , while the observed rates are much lower ( $\sim 5M_{\text{sun}} \text{ yr}^{-1}$ ; see, e.g., Stahler & Palla 2004), suggesting that the star formation efficiency (SFE) is reduced by some mechanism. The observed SFE ranges from a few percent when whole giant molecular complexes are considered (e.g., Myers *et al.* 1986), to 10–30% in cluster-forming cores (e.g., Lada & Lada 2003).

The SFE in MCs, defined as the fraction of the clouds' mass that finally makes it into a star during their lifetime, can be simply written as  $\text{SFE} = \text{SFR} \times \Delta\tau_{\text{c}}$ , where SFR is the star formation rate, and  $\Delta\tau_{\text{c}}$  is the cloud lifetime. Thus, a low SFE can be obtained

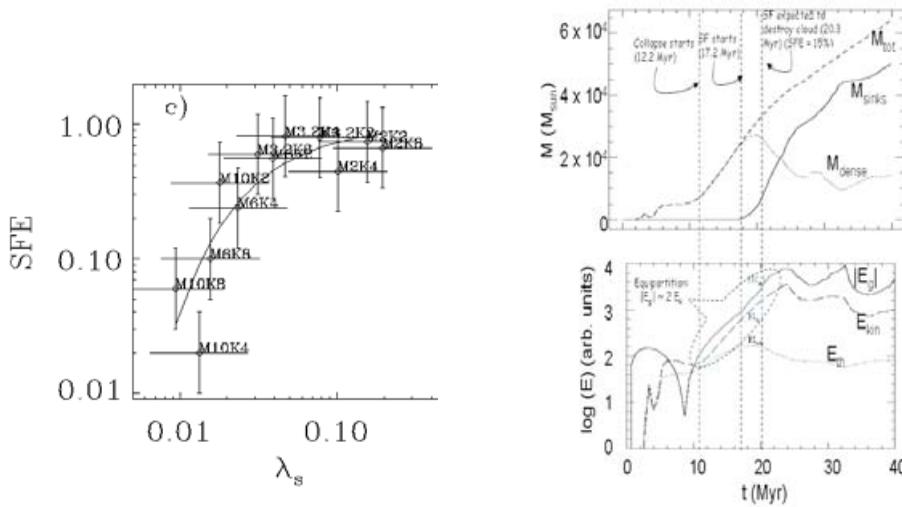
through either a small  $\Delta\tau_c$  or a low SFR. Currently, there is an ongoing debate within the community on whether the cloud lifetimes are long, but the SFR is small (or even zero) over a major fraction of the cloud lifetime (e.g. Palla & Stahler 2000; Palla & Stahler 2002; Tassis & Mouschovias 2004; Mouschovias, Tassis & Kunz 2006; Tan, Krumholz & McKee 2006), or else the lifetimes are short, but the SFRs are relatively large (e.g., Ballesteros-Paredes, Hartmann & Vázquez-Semadeni 1999; Klessen, Heitsch & Mac Low 2000; Hartmann, Ballesteros-Paredes & Bergin 2001, hereafter HBB01; Hartmann (2003); Bate, Bonnell & Bromm 2003; Bonnell & Bate 2006; Ballesteros-Paredes & Hartmann 2006; Vázquez-Semadeni *et al.* 2006b).

MCs are also known to have supersonic linewidths, which have been attributed to turbulent motions (e.g., Zuckerman & Evans 1974; Larson 1981; Blitz 1993). Turbulent flows are characterized by a scaling of the typical velocity difference  $\Delta v$  across points separated by a distance  $\ell$  that scales as  $\Delta v \propto \ell^\alpha$ , with  $\alpha > 0$  (e.g., Lesieur 1990), implying that the largest velocity differences occur at the largest spatial scales of a given cloud or clump (Larson 1981). Thus, turbulence is expected to have a *dual* role in the dynamics of MCs (e.g., Vázquez-Semadeni & Passot 1999; Mac Low & Klessen 2004; Ballesteros-Paredes *et al.* 2006): On the one hand, with respect to regions of size  $L$ , supersonic compressive turbulent modes of size  $\ell > L$  will act mainly as pistons that can form a density peak (a “cloud”, “clump” or “core”) out of those regions. The timescale for clump formation is essentially the turbulent crossing time across scale  $\ell$ . Since the compressions are supersonic, this is typically shorter than the free-fall or sound-crossing times. On the other hand, turbulent modes with  $\ell < L$  will provide support against the self-gravity of a clump of size  $L$ .

In this paper we review recent numerical results concerning the effect of the molecular cloud turbulence and the magnetic field on the regulation of the SFE, and discuss how the resolution of certain issues, such as the determination of the most appropriate set of parameters requires studying the formation of the clouds themselves. This review extends the one presented earlier by Vázquez-Semadeni (2005).

## 2. Effect of the driving scale and turbulent Mach number on the SFE

Results from numerical simulations in the recent past have shown that the effect of the rms Mach number of the turbulence  $\mathcal{M}_s$  on the SFE depends on whether the turbulence is driven or decaying. In continuously driven regimes in closed boxes, with periodic boundary conditions and a fixed total mass, Klessen *et al.* (2000) showed that the SFE decreases systematically as either the driving scale of the turbulence  $\lambda_d$  is decreased, or the turbulent Mach number  $\mathcal{M}_s$  is increased, and Vázquez-Semadeni, Ballesteros-Paredes & Klessen (2003) subsequently showed that the dependence on  $\mathcal{M}_s$  and  $\lambda_d$  could be combined into the dependence with one single parameter, the *sonic scale*  $\lambda_s$  of the turbulence. This is the scale at which the typical turbulent velocity fluctuation (which decreases with scale) equals the sound speed, and is related to  $\mathcal{M}_s$  and  $\lambda_d$  by  $\lambda_s \approx \lambda_d \mathcal{M}_s^{-1/\alpha}$ , where  $\alpha$  is the exponent in the velocity dispersion-size relation (cf., §1). At a fixed number of Jeans masses, reducing  $\lambda_s$  leads to a reduction of the fraction of the total mass in scales smaller than  $\lambda_s$ , and the SFE is expected to decrease. Indeed, Vázquez-Semadeni *et al.* (2003) were able to empirically fit a functional dependence of the form  $\text{SFE} \propto \exp(-\lambda_0/\lambda_s)$ , with  $\lambda_0 \sim 0.11$  pc in the simulations they studied (fig. 1, *left panel*). From the above relation, this translates into  $\text{SFE} \approx \exp(-\lambda_0 \mathcal{M}_s^{1/\alpha}/\lambda_d)$ , implying that, at fixed  $\lambda_d$ ,  $\lambda_s$  decreases with increasing  $\mathcal{M}_s$  in driven regimes. This can be understood in terms of the net effect of the turbulent velocity fluctuations, which on



**Figure 1.** *Left panel:* Star formation efficiency SFE vs. sonic scale  $\lambda_s$  for runs with various rms Mach numbers ( $M$ ) and turbulence driving wavenumbers  $K$ , indicated for each point (from Vázquez-Semadeni *et al.* 2003). *Right panel:* Evolution of the dense gas mass,  $M_{\text{dense}}$ , mass in stellar objects  $M_{\text{sinks}}$ , and total mass  $M = M_{\text{dense}} + M_{\text{sinks}}$  (*top*) and the gravitational, kinetic and thermal energies (resp.  $E_g$ ,  $E_k$  and  $E_{\text{th}}$ ) for a simulation of colliding WNM streams in the presence of thermal bistability and self-gravity (*bottom*, from Vázquez-Semadeni *et al.* 2006b).

the one hand produce larger-amplitude density fluctuations, but on the other increase the effective “sound” speed in the flow, giving the net result that the effective Jeans mass  $M_{J,\text{eff}}$  scales with the rms Mach number as

$$M_{J,\text{eff}} \propto \mathcal{M}_s^2 \tag{2.1}$$

(Mac Low & Klessen 2004, sec. IV.G). At larger  $M_{J,\text{eff}}$  it becomes increasingly difficult to collect a core more massive than this mass that can proceed to collapse.

In contrast, in decaying regimes, the SFE appears to *increase* with the rms Mach number of the initial velocity fluctuations (Nakamura & Li 2005). This can be understood because, in this regime, the initial velocity fluctuations can still perform the same fast clump-forming role as in driven regimes. However, at later times, the global decay of the turbulence implies that its supporting action is gradually lost, and  $M_{J,\text{eff}}$  decreases, as indicated by eq. (2.1) for  $\mathcal{M}_s$  decreasing over time.

In either case, the efficiencies obtained in non-magnetic numerical simulations still appear larger than observational values. For example, Vázquez-Semadeni *et al.* (2003) reported an SFE  $\sim 30\%$  in a driven simulation with  $\mathcal{M}_s = 10$  and a mass  $M = 64M_J$  ( $= 1860M_{\text{sun}}$ ), where  $M_J$  is the thermal Jeans mass, while a two-dimensional decaying simulation with *initial*  $\mathcal{M}_s = 10$  and  $M = 100M_J$  reported by Nakamura & Li (2005) reached SFE  $\sim 60\%$ . Note also that the latter simulation actually had already decayed to  $\mathcal{M}_s \sim 2\text{--}3$  by the time it was forming stars, a value that appears too low compared with typical turbulent Mach numbers observed in clouds (e.g., Blitz 1993).

### 3. Effect of the magnetic field strength on the SFE

The magnetic field is an important physical ingredient of interstellar dynamics, and may contribute towards further reducing the SFE obtained in simulations to levels more consistent with observations, even in magnetically supercritical regimes.

In the magnetic case, a fundamental control parameter is the mass-to-magnetic flux ratio  $\mu$  (in units of the critical value for magnetic support against collapse). Under ideal MHD conditions, supercritical cases ( $\mu > 1$ ) can undergo gravitational collapse, while subcritical cases ( $\mu < 1$ ) are unconditionally supported against it. In this case, collapse can only occur if a Lagrangian fluid parcel loses some of its magnetic flux through some dissipative or diffusive process, such as ambipolar diffusion (AD; e.g., Mestel & Spitzer 1956).

Numerical simulations show that, in magnetically supercritical simulations, collapse is in general delayed with respect to the non-magnetic case (Ostriker, Gammie & Stone 1999; Heitsch, Mac Low & Klessen 2001; Vázquez-Semadeni *et al.* 2005; Nakamura & Li 2005). Recently, the SFE has been measured in simulations of 3D, driven, supercritical simulations of ideal MHD (Vázquez-Semadeni *et al.* 2005) and decaying, 2D simulations including AD (Nakamura & Li 2005). Realistic values of the SFE at the level of whole clouds (SFE  $\sim$  a few percent) required moderately subcritical regimes in the decaying cases, but only moderately supercritical regimes in the driven simulations, evidencing again the distinction between driven and decaying regimes. Stronger fields are needed in decaying conditions to compensate for the systematic loss of turbulent support.

In any case, both types of studies show that the SFE is reduced by the presence of a magnetic field even in supercritical regimes, with a tendency to greater reductions at larger mean field strengths. This suggests that the effect of the magnetic field on attenuating the SFE may be gradual rather than dichotomic, as was the case of the distinction between the sub- and supercritical regimes advanced by the “standard” model of magnetic support (e.g., Mouschovias 1976; Shu *et al.* 1987).

### 4. Discussion: A bigger question

In the previous sections we have summarized results on the SFE in a variety of contexts: driven vs. decaying simulations, and magnetic versus non-magnetic. The main conclusions to be drawn from the existing results are that (1) the very effect of the intensity of the turbulence (measured by the rms Mach number  $\mathcal{M}_s$ ) depends on whether the turbulence is driven or decaying, and (2) the efficiency is reduced as the magnetic field increases from zero to supercritical levels to subcritical levels, but the values of the magnetic field strength needed to attain realistic values of the SFE again depend on whether the turbulence is driven or decaying. Thus, the behavior of the SFE with the parameters  $\mathcal{M}_s$  and  $\mu$  is relatively well understood, but it is necessary to determine what is the true nature of the turbulence driving in molecular clouds (driven, decaying, or somewhere in between) in order to assess the response of the SFE to the parameters.

It is also important to note that in all the simulations described above, it is necessary to define a certain time at which to terminate the accounting of the mass deposited in collapsed objects. This time is typically a few to several free-fall times (a few Myr). If left to run for arbitrarily long times, most of these simulations would eventually turn most of their gas into stars. It is therefore also necessary to address the MC lifetime problem in order to understand the SFE. Presumably, accomplishing both tasks (determining the nature of the driving and the clouds’ lifetimes) amounts to addressing the questions of

how the clouds themselves form and acquire their properties, and how they are eventually dispersed; that is, their full life cycle.

## 5. Simulations of cloud formation and evolution

### 5.1. Results

The question of whether the turbulence is driven or decaying is unsettled at present. Arguments in favor of continuous driving include the fact that even nearly starless MCs such as Maddalena's cloud have similar turbulent parameters as clouds with healthy star formation rates (Maddalena & Thaddeus 1985), and that CO clouds fall on a tight velocity dispersion-size relation suggestive of a single cascade process operating at scales ranging from  $\sim 100$  pc to  $\lesssim 0.1$  pc in the ISM (e.g., Larson 1981; Heyer & Brunt 2004; see also Breitschwerdt, this volume). Also, the energy feedback from stellar sources once they have started forming is thought to be able to possibly maintain the turbulence in the clouds (e.g., Matzner 2002; Tan, Krumholz & McKee 2006; Krumholz, Matzner & McKee 2006; Li & Nakamura 2006), or even disperse them altogether (e.g., Franco, Shore & Tenorio-Tagle 1994; HBB01; Ballesteros-Paredes 2004).

Recently, it has been proposed that MCs may acquire at least their initial levels of turbulence from the very accumulation process that forms the cloud (Vázquez-Semadeni, Ballesteros-Paredes & Klessen 2003; Heitsch *et al.* 2005; Vázquez-Semadeni *et al.* 2006a, 2006b; Heitsch *et al.* 2006; see also Koyama & Inutsuka 2002; Inutsuka & Koyama 2004), through a combination of the thermal instability and various dynamical instabilities in the compressed layer between converging flows. The precise nature of the instability at work is not yet agreed upon.

These studies have shown that the collision of warm neutral medium (WNM) streams at transonic velocities in the absence of self-gravity produces velocity dispersions of several  $\text{km s}^{-1}$ , typical of molecular clouds. Furthermore, Vázquez-Semadeni *et al.* (2006a) also showed that the pressure in the dense ( $n > 100 \text{ cm}^{-3}$ ) gas is larger than the mean WNM pressure by factors 1.5–5, due to the ram pressure of the compressive motion that forms the clouds. These results suggest that cloud formation by WNM stream collisions or passing shocks can produce the observed turbulent velocity dispersions in MCs and at least part of their excess pressure.

Most relevant for our discussion here are the facts that in those studies the turbulence is driven for as long a time as the inflow that forms the cloud persists, and that the rms Mach number of the turbulence in the dense gas depends on the Mach number of the inflow (see also Folini & Walder 2006). This means that, at least during the early epochs of a molecular cloud's existence, the turbulence may be driven, albeit presumably the driving rate itself is decaying, as the inflows that form the cloud subside, and, eventually, the cloud may be left in a decaying state.

This mechanism has been recently investigated including self-gravity and a sink particle prescription for treating collapsed objects by Vázquez-Semadeni *et al.* (2006b). This study has shown that, within its framework and limitations (magnetic fields, stellar energy feedback and chemistry were not included), the clouds evolve secularly, rather than achieving a quasi-stationary state. The collision of WNM streams nonlinearly triggers thermal instability and a transition to the cold neutral medium. Due to the ram pressure of the inflows, densities and temperatures overshoot to values typical of molecular gas. The dense gas (the "cloud") evolves by continuing to incorporate mass, generating an increasingly deep gravitational potential well in the process. Eventually, the gravitational energy  $E_g$  of the cloud overwhelms the thermal+turbulent energies ( $E_{\text{th}}$  and  $E_k$ ) and the

cloud begins to contract gravitationally. This process is illustrated in fig. 1 (*right panel*), which shows the evolution of the dense gas and stellar mass in the simulation, along with the various energies for a simulation in a cubic box of 256 pc per side, in which a cloud is formed by the collision of two oppositely-directed WNM streams at speeds of  $\pm 9.2 \text{ km s}^{-1}$ , and each with a length of 112 pc and a radius of 32 pc.

In this simulation,  $E_g$  is seen to become dominant at  $t \sim 12 \text{ Myr}$ , but the kinetic energy is “dragged along” by the gravitational contraction, with the result that there is near equipartition between the two throughout the collapse, in agreement with observations. After some delay (at  $t \sim 17 \text{ Myr}$  for this simulation), local collapse events begin to occur, and within three more Myr ( $t \sim 20 \text{ Myr}$ ),  $\sim 15\%$  of the cloud’s mass ( $\sim 5000 M_{\text{sun}}$ ) has been converted to stars, at a mean rate  $\sim 1.7 \times 10^{-3} M_{\text{sun}} \text{ yr}^{-1}$ . In the simulation, this rate continues for another  $\sim 5 \text{ Myr}$  (to  $t \sim 25 \text{ Myr}$ ), but already by  $t \sim 20 \text{ Myr}$ , the mass that has been converted to stars implies that enough OB stars should be present to destroy the cloud (Franco, Shore & Tenorio-Tagle 1994), assuming a standard IMF. The SFE in this simulation at this time ( $\sim 15\%$ ) is thus comparable to that in the simulations of gravitationally bound clouds discussed in §2. But, as in all those simulations, this is dependent on the assumption that the cloud somehow ceases to form stars some 3–5 Myr after it started.

## 5.2. Implications

Some important consequences of this scenario for MC formation should be noted. First, even though a long delay ( $\sim 15 \text{ Myr}$ ) occurs between the beginning of the formation process (the time at which the collision between the WNM streams begins), the cloud is expected to remain atomic during most of this time, since the cloud’s mean column density is only reaching typical values for molecule formation ( $\sim 10^{21} \text{ cm}^{-2} \sim 8 M_{\text{sun}} \text{ pc}^{-2}$ ; see Franco & Cox 1986; HBB01 and references therein; Blitz, this volume) by the time it is beginning to form stars. Thus, even though the cloud as a density enhancement lives  $\sim 20 \text{ Myr}$ , its *molecular* stage is expected to comprise only the last few Myr. That is, there may indeed be a long “dormancy” period before the onset of star formation as suggested by various groups (e.g., Palla & Stahler 2000, 2002; Goldsmith & Li 2005; Mouschovias *et al.* 2006), but most likely it is spent in an atomic, growing state, rather than in a molecular, quasi-equilibrium one.

Second, this scenario of molecular cloud formation implies that the mass-to-flux ratio of the cloud is a variable quantity as the cloud evolves. This ratio is equivalent to the ratio of column density to magnetic field strength (Nakano & Nakamura 1978), with the critical column density given by  $\Sigma \sim 1.5 \times 10^{21} [B/5\mu G] \text{ cm}^{-2}$ . Although in principle under ideal MHD conditions the criticality of a magnetic flux tube involves *all* of the mass contained within it, in practice it is only the mass in the dense gas phase that matters, because the diffuse gas is not significantly self-gravitating at the size scales of MC complexes. As pointed out by HBB01, the above value of the dense gas’ column density is very close to that required for gravitational binding, and therefore, the cloud is expected to become magnetically supercritical nearly at the same time it is becoming molecular and self-gravitating. This is consistent with the results of the simulations by Vázquez-Semadeni *et al.* (2006b), in which the column densities of the first four regions to form stars were measured to have column densities within a factor of two of  $N = 10^{21} \text{ cm}^{-2}$  immediately before the first local collapse event occurred there.

Finally, the results from the simulations by Vázquez-Semadeni *et al.* (2006b) would seem to suggest a return to the Goldreich & Kwan (1974) scenario of global gravitational collapse in MCs, except that the criticism by Zuckerman & Palmer (1974) would be avoided in part because the nonlinear turbulent density fluctuations collapse earlier than

the whole cloud, involving only a fraction of the total mass, and in part because as soon as the stars form they probably contribute to dispersing the cloud, or at least halting its global collapse. This is consistent with the recent suggestion by Hartmann & Burkert (2006) that the Orion MC may be undergoing global gravitational collapse.

## 6. Conclusions

We conclude that numerical simulations of isolated clouds up to the present have quantitatively constrained the effect of the turbulent Mach number and the magnetic field strength on the SFE, but in turn this effect depends on the nature of the turbulence production and maintenance, and on the lifetimes of the clouds themselves. Simulations of MC formation within their diffuse environment have begun to shed light on these issues, but much parameter space exploration and inclusion of additional physics (notably, magnetic fields and stellar energy feedback) remain to be done.

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## Discussion

CLARK: You say that the final SFE in your simulation is  $\sim 15\%$ , which is too high. Have you tried unbound clouds (kinetically) to see whether the final SFE goes down?

VÁZQUEZ-SEMADENI: In this simulation the boundedness of the cloud is produced self-consistently by the cloud-formation process, so we do not control it directly. In this particular simulation, the resulting cloud is strongly bound. Nevertheless, one could try to produce a less strongly bound cloud, or even unbound, by decreasing the mass contained in the inflowing streams, or increasing their speed. We are currently performing a parameter study to investigate different cloud masses and inflow velocities.

ROSOLOWSKY: Could you comment on the applicability of your simulations to the formation of GMCs, specifically in the case where the scales over which you have to gather gas become significant on a galactic scale?

VÁZQUEZ-SEMADENI: I am convinced that the process of compression, then cooling with turbulence generation, and finally gravitational collapse, should be representative of GMC formation in spiral arms, although modeling the process more accurately should incorporate the vertical stratification as well.