How turbulence and magnetic fields set the rate of collapse in molecular clouds

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Abstract and introduction. An important question in star formation is the degree to which initial turbulent conditions dominate the formation and collapse of prestellar cores. Different scenarios in the literature invoke either

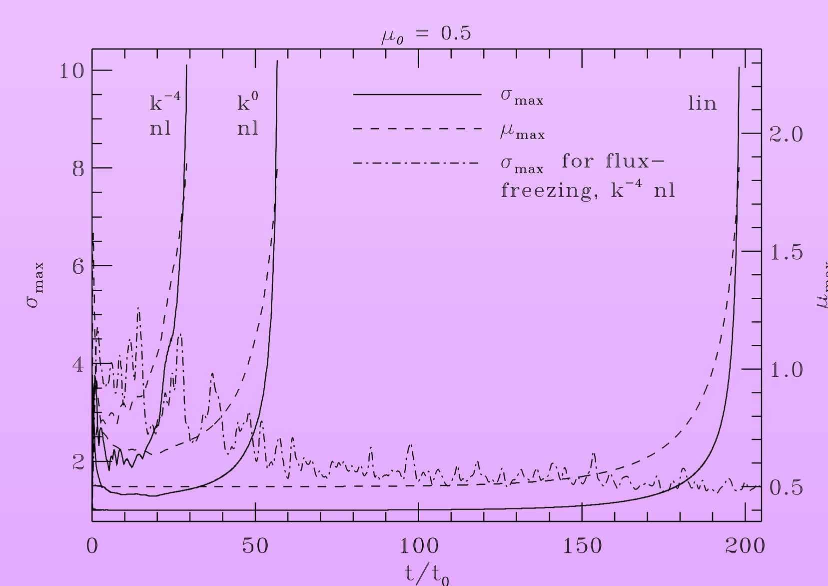
(1) turbulent energy that dominates the magnetic energy (super-Alfvénic turbulence), or

(2) comparable magnitudes of the two energies (trans- or mildly sub-Alfvénic turbulence).

We compare these scenarios using simulations that model self-gravity, magnetic fields including ambipolar diffusion, and 'turbulent' nonlinear flows that are allowed to decay freely. We explore the effects of different power spectra and amplitudes of the initial velocity field, initial mass-to-magnetic-flux ratios, and neutral-ion collision times (i.e. the level of coupling), and provide physical explanations of how these lead to different outcomes. Super-Alfvénic initial conditions cause prompt collapse in less than a dynamical time, while less turbulence yields gravitational collapse of the first core(s) within a few dynamical times in strongly magnetized clouds. We find observationally-distinguishable differences between models, and argue that these rule out super-Alfvénic turbulent flows as an agent of fragmentation. In contrast, trans-Alfvénic motions not only reduce the time scales of magnetically-regulated star formation to generally accepted values, but also produce core and infall velocities more consistent with observations.

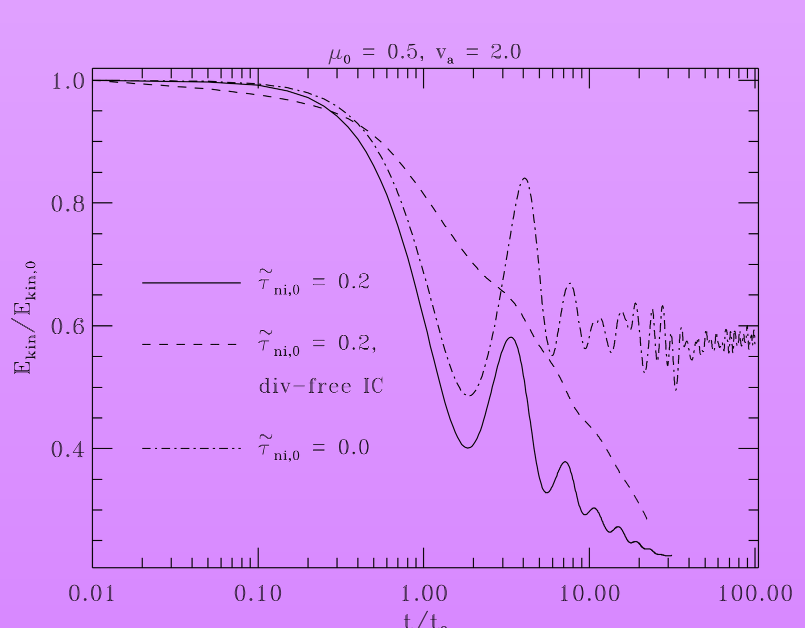
Overview. We have performed a parameter study of fragmentation of a dense layer within a molecular cloud aided by the presence of initial nonlinear velocity perturbations, in an isothermal thin-sheet model, including magnetic fields and ambipolar diffusion. It is currently not possible to cover the whole parameter space in 3-dimensional non-ideal MHD simulations, but some of the main results have been confirmed by Kudoh and Basu (2008). We ran each of our models 10-15 times with equivalent but random initial conditions.

Varying turbulence power spectra. In most models, the power spectrum of fluctuations is $\propto k^{-4}$, where the initial conditions (ICs) impose primarily a large-scale flow to the system. We have also studied the case of nonlinear perturbations with power spectrum $\propto k^0$, in which the small-scale fluctuations play a bigger role. Of the two modes, the latter is more similar to gravitational fragmentation arising from small-amplitude perturbations (see Basu et al. 2009). The main difference is an accelerated time scale for core formation. This is particularly apparent for the cases with subcritical initial mass-to-flux ratio, in which case the nonlinear fluctuations enhance ambipolar diffusion (see Fatuzzo and Adams, 2002; Zweibel, 2002). We found a speedup of x7 (for k^{-4}) and x4 (for k^0).



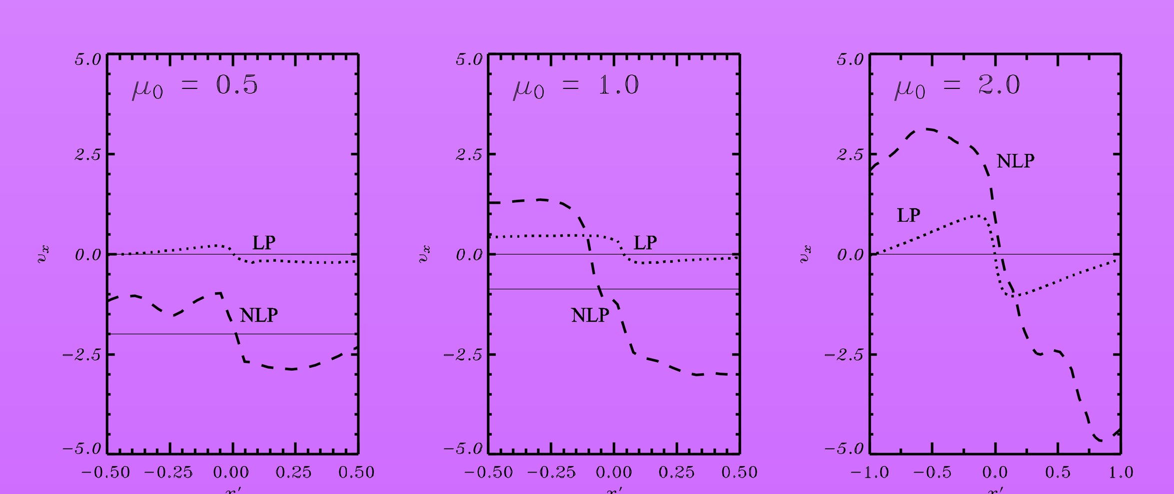
- nonlinear initial perturbations decrease the timescale of runaway collapse compared to linear ICs
- k^{-4} introduces a dominant large-scale mode, and leads to the most rapid collapse
- k^0 has equal power on all scales, and yields less speedup than k^{-4} ICs.

Varying levels of coupling. Another parameter whose effect we investigated is the neutral-ion collision times. Model 1 (see Table 1) shows the case of flux-freezing. In this case, the subcritical cores cannot collapse, since magnetic forces dominate over gravity. In the case of imperfect coupling (models 4, 10, and 11), ambipolar diffusion is more effective the better the coupling is, and the time to gravitational runaway collapse gets shorter with increasing $\tau_{ni;0}$ (see Table 1).



- while both compressive and incompressive nonlinear perturbations aid and speed up collapse, the subcritical flux-freezing case cannot collapse at all.
- Some kinetic energy is maintained in long-lived large-scale oscillations in that case

Varying mass-to-flux ratio. We explored different outcomes with varying initial mass-to-flux ratios (models 4, 13, and 17). For weak magnetization, even moderate turbulent flows can overpower the magnetic support, causing prompt collapse (see Table 1). In this case, infall on the cores is supersonic. In the subcritical and transcritical cases, the cores gain a systematic speed.



- supersonic infall for super-magnetosonic perturbations
- subsonic infall for sub-magnetosonic perturbations

Model No.	μ_0	$\tau_{ni;0}$	Spectrum	v_a/c_s	$v_{MS;0}/c_s$	t_{run}/t_0
1	0.5	0.0	k^{-4}	2.0	2.9	> 5000
2	0.5	0.2	k^{-4}	4.0	2.9	0.8
3	0.5	0.2	k^{-4}	3.0	2.9	30
4	0.5	0.2	k^{-4}	2.0	2.9	31
8	0.5	0.2	k^{-4} (div0)	2.0	2.9	23
9	0.5	0.2	k^0	2.0	2.9	56
10	0.5	0.1	k^{-4}	2.0	2.9	92
11	0.5	0.4	k^{-4}	2.0	2.9	8.1
13	1.0	0.2	k^{-4}	2.0	1.7	1.8
17	2.0	0.2	k^{-4}	2.0	1.2	1.3

Table 1: models and parameters.

Prompt collapse occurs when $v_a > v_{MS;0}$

mass-to-flux ratio $\mu_0 = 2\pi G^{1/2}\,\sigma_{n,0}/B_{ref}$

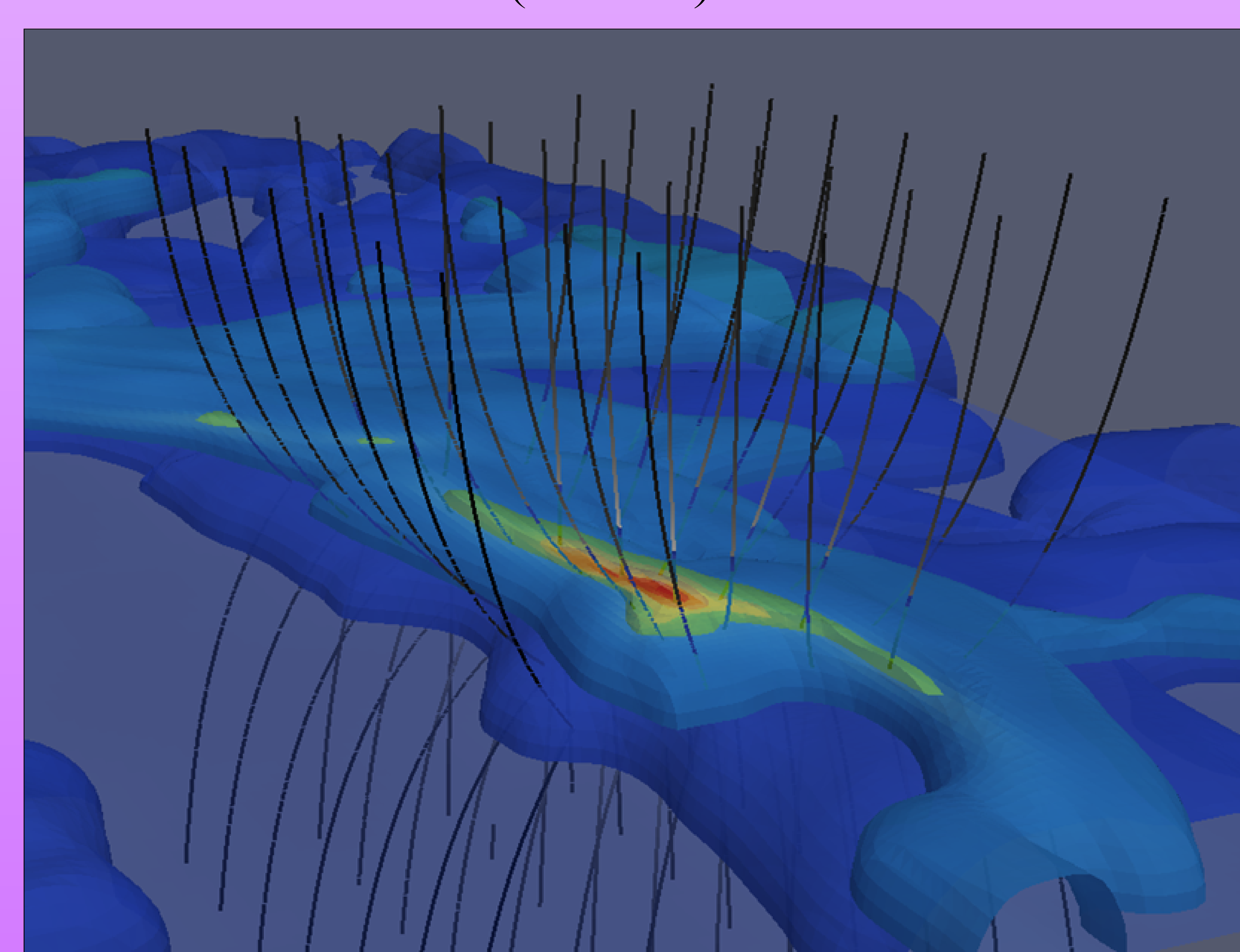
neutral-ion collision time $\tilde{\tau}_{ni;0} = \tau_{ni;0}/t_0$ with $t_0 = c_s/2\pi G\sigma_{n,0}$

$\tilde{\tau}_{ni;0} = 0.2$ corresponds to ionization fraction $\chi_i = 10^{-7}\left(\dfrac{n_n}{10^4\ \mathrm{cm}^{-3}}\right)^{-1/2}$

$v_a =$ initial amplitude of nonlinear perturbations

$v_{MS;0} =$ initial magnetosonic speed

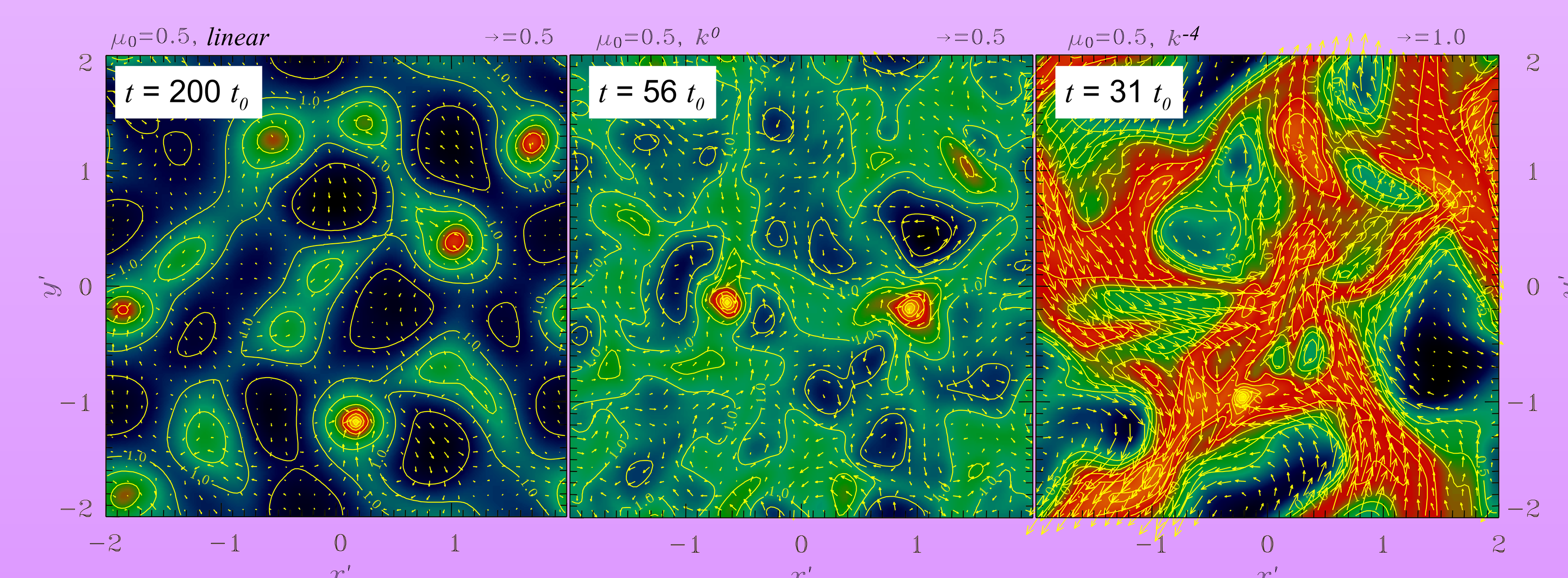
$$t_0 = 3.65\times10^4\left(\frac{T}{10\,\mathrm{K}}\right)^{1/2}\left(\frac{10^{22}\ \mathrm{cm}^{-2}}{N_{n,0}}\right)\mathrm{yr}$$



- 3D view of our simulation assuming a hydrostatic vertical structure, and a force-free magnetic field above the sheet.
- the magnetic field lines exhibit an hour-glass configuration curving towards the high-density peak
- filamentary structure of the core is apparent

Varying 'turbulent' amplitudes, prompt collapse. For the case of nonlinear-flow-induced fragmentation, originally studied by Li and Nakamura (2004) and Nakamura and Li (2005), we find that cores go into direct collapse for supercritical clouds. For critical, and more so for subcritical clouds, the initial compression may be followed by a rebound and oscillations which eventually lead to runaway collapse in dense pockets where enhanced ambipolar diffusion has created supercritical conditions. What determines the outcome? For any given field strength, there is a threshold initial velocity amplitude v_a above which prompt collapse will take place. An examination of model outcomes in Table 1 reveals that, for a fixed standard initial ionization fraction defined by $\tilde{\tau}_{ni;0} = 0.2$, prompt collapse takes place when $v_a > v_{MS;0}$ (models 2, 13, and 17). Indeed model 3, which has $v_a \approx v_{MS;0}$ is actually prone to go into prompt collapse ($t_{run} \approx t_0$) in some realizations, but undergoes several oscillations before runaway collapse in most cases (with representative value $t_{run} \approx 30\,t_0$). We can say that significantly super-Alfvénic perturbations are associated with prompt collapse, for both subcritical and supercritical model clouds. This criterion does not apply to models with initial power spectrum $\propto k^0$, since the kinetic energy does not get channeled toward a large-scale compression wave.

Structure of cores. The highly filamentary structure of clouds in which prompt collapse takes place is a source of concern when comparing with maps of observed molecular clouds. This was noted by Li and Nakamura (2004), who commented that clouds with weak magnetic field and supersonic turbulence with a power spectrum having most power on the largest scales would appear too filamentary in comparison with observations. Our study extends this concern also to models with strong magnetic field if the turbulence is highly super-Alfvénic, since prompt collapse occurs in highly compressed filaments without a chance for them to rebound. Since the weak magnetic field cases also have by design a velocity amplitude that is super-Alfvénic, we can say that super-Alfvénic turbulence in all cases may have problems with excessive filamentarity.



Core kinematics. There is another problem with large amounts of turbulent forcing: the relative infall motions onto the cores are highly supersonic, and at odds with observed core infall motions (Tafalla et al., 1998; Williams et al., 1999; Lee et al., 2001; Caselli et al., 2002), which are subsonic or at best transonic. Of course, both of these problems are set up artificially in our simulations through nonlinear forcing associated with the initial conditions. In other simulations of driven super-Alfvénic turbulence (Padoan and Nordlund, 2002), such forcing continues at all times and the above features are always present.

Summary.

- nonlinear initial perturbations can speed up the process of fragmentation in the presence of magnetic fields to observationally-supported time scales.
- this speedup occurs for compressive and incompressive initial velocity fields
- in the flux-freezing case, collapse cannot occur, and long-lived large-scale oscillations arise instead. In this case, the turbulent energy does not decay completely, but some remains in the system
- turbulence with most power on the largest scales is more effective in reducing the time to runaway collapse
- super-Alfvénic ICs cause self-gravitating density enhancements which go into prompt collapse on time scales of less than a dynamical time.
- super-Alfvénic ICs also cause extreme filamentarity and highly supersonic infall speeds onto cores, both generally at odds with observations