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# THE LIFETIMES OF MOLECULAR CLOUD CORES: WHAT IS THE ROLE OF THE MAGNETIC FIELD?

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RESUMEN

Discutimos los tiempos de vida y la evolución de los núcleos densos formados como fluctuaciones turbulentas de densidad en nubes moleculares isotérmicas magnetizadas. Consideramos simulaciones numéricas en las que medimos la criticalidad magnética y la estabilidad de Jeans de los núcleos, en relación a la criticalidad magnética de sus nubes "madre" (los dominios de integración numérica). En dominios subcríticos, no se forman núcleos densos, y no ocurre colapso gravitacional. En dominios supercríticos, algunos núcleos se colapsan, formando parte de grumos más grandes que son supercríticos desde el inicio, y cuyas regiones más densas (los núcleos) son inicialmente subcríticas, pero rápidamente se tornan supercríticos, presumiblemente por acreción a lo largo de las líneas de campo magnético. Descartamos la posibilidad de artefactos numéricos. Las escalas de tiempo en las que los núcleos transitan desde el estado subcrítico, pasando por el supercrítico, hasta finalmente el colapso, son de unas cuantas veces su tiempo de caída libre, $\tau_{\rm fc}$. Nuestros resultados sugieren que los núcleos son estructuras transientes, fuera de equilibrio, y no configuraciones cuasi-magneto-hidrostáticas.

ABSTRACT

We discuss the lifetimes and evolution of dense cores formed as turbulent density fluctuations in magnetized, isothermal molecular clouds. We consider numerical simulations in which we measure the cores' magnetic criticality and Jeans stability in relation to the magnetic criticality of their "parent clouds" (the numerical boxes). In subcritical boxes, dense cores do not form, and collapse does not occur. In supercritical boxes, some cores collapse, being part of larger clumps that are supercritical from the start, and whose central, densest regions (the cores) are initially subcritical, but rapidly become supercritical, presumably by accretion along field lines. Numerical artifacts are ruled out. The time scales for cores to go from subcritical to supercritical and then collapse are a few times the core free-fall time, $\tau_{\rm fc}$. Our results suggest that cores are out-of-equilibrium, transient structures, rather than quasi-magnetostatic configurations.

*Key Words:* **ISM: CLOUDS — ISM: MOLECULES — ISM: TURBULENCE — STARS: FORMATION**



## 1. INTRODUCTION

The prevailing view (which we hereafter refer to as the "standard (magnetic support) model" of star formation; see, e.g., the reviews by Shu, Adams & Lizano 1987; McKee et al. 1993) concerning low-mass-star-forming clumps is that they are quasi-static equilibrium configurations with so-called "subcritical" mass-to-magnetic-flux ratios, so that the clumps are supported against their self-gravity by the magnetic field in the direction perpendicular to it, and by a combination of thermal and turbulent pressures along the field. Under ideal MHD conditions, the magnetic field is "frozen" into the plasma, and the magnetic flux is conserved. Under the additional assumption that the clump's mass is also constant, then the mass-to-flux ratio is a fixed parameter of the clump, which therefore cannot collapse if this ratio is subcritical (meaning that the core's self-gravity is never enough to overwhelm the magnetic support). However, because the cold molecular gas is only partially ionized, the process known as ambipolar diffusion causes a loss of magnetic flux from the clumps on time scales long compared to their free-fall time, allowing them to contract and form denser cores that will ultimately collapse.

However, it well known that molecular clouds are supersonically turbulent (e.g., Larson 1981; Blitz & Williams 1999), and it is becoming increasingly accepted that the cores within them are the density fluctuations induced by the turbulence (Ballesteros-Paredes, Vázquez-Semadeni & Scalo 1999; see also the reviews by Vázquez-Semadeni et al. 2000; Mac Low & Klessen 2004). In this context, the cores have a highly dynamical origin (supersonic compressions), and their masses are hardly fixed. Moreover, it is natural to ask whether they can settle into hydro-

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static equilibria, an event which requires the equilibria to be stable (or "attracting", in the language of nonlinear phenomena). Otherwise, the dynamic density fluctuations will just "fly past" the equilibrium state on their way to collapse, or else "rebound" and merge back with their environment, if they do not quite reach the equilibrium point. In this case, the cores' lifetimes should be much shorter than in the standard model, probably comparable to their free-fall times. In the present contribution, we argue in favor of this scenario. To this end, we discuss the formation and evolutionary time scales of cores that form in numerical simulations of isothermal, compressible MHD turbulence, in relation to the magnetic criticality of the whole computational box. Here we present a brief overview. For a full, detailed discussion, see Vázquez-Semadeni et al. (2004).

## 2. QUALITATIVE CONSIDERATIONS

For the discussion below, it is convenient to characterize a core by two non-dimensional parameters: its *Jeans number* $J_c = R_c/L_J$, giving the ratio of the core's radius $R_c$ to its Jeans length $L_J$, so that a gravitationally unstable core (with respect to thermal support) has $J_c > 1$, and its mass-to-flux ratio $\mu_c$, normalized to the critical value for magnetic support, so that a supercritical structure has $\mu_c > 1$. The corresponding values for the entire computational box are denoted $J$ and $\mu$.

To assess the necessary conditions for the formation of either sub- or supercritical cores, we note that the mass-to-flux ratio of an *isolated* cloud constitutes an upper bound for that of any subregion within it, since, as long as the flux-freezing condition holds, both the cloud's mass and magnetic flux are fixed, regardless of the cloud's volume. So, even if the entire mass of the cloud were compressed into the core's volume, its mass-to-flux ratio would remain the same. Thus, in the absence of ambipolar diffusion, supercritical cores can only form within supercritical clouds or clumps. On the other hand, subcritical cores can arise in either sub- or supercritical clouds. Now, a *gravitationally bound*, yet subcritical clump must have $J_c > 1$ in addition to $\mu_c < 1$, so that it does not re-expand after the turbulent compression that formed it subsides. However, recent observational studies of the magnetic field strengths in molecular clouds suggest that these are the objects with highest mass-to-flux ratio in the hierarchy going from diffuse clouds to dense cores (e.g., Crutcher 2004), and are likely to be supercritical in general (e.g., Bourke et al. 2001), so the formation of supercritical cores without the need for ambipolar diffusion appears feasible in real molecular clouds.

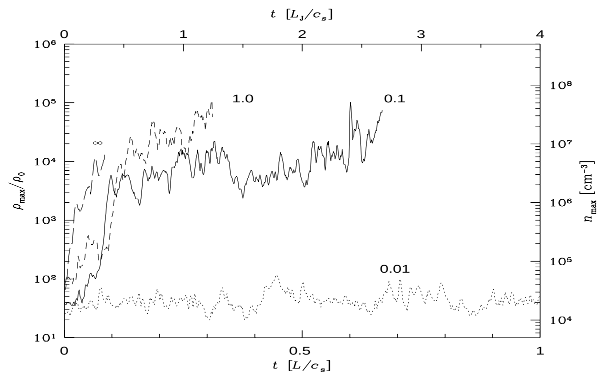


Fig. 1. Evolution of the global maximum of the density field for all runs considered here. The numbers indicate the corresponding values of $\beta$.

## 3. NUMERICAL SIMULATIONS AND RESULTS

In order to investigate the magnetic criticality of the cores that can form in turbulent environments in relation to that of their parent clouds, we have performed a suite of numerical simulations of turbulent flows at fixed rms sonic Mach number ($M_s \sim 10$) and *global* Jeans number $J = 4$, and varying the plasma $\beta$, defined as the ratio of thermal to magnetic pressure, in order to consider cases that are subcritical (denoted $\beta.01$, with $\mu = 0.9$), mildly supercritical (denoted $\beta.1$, with $\mu = 2.8$), strongly supercritical (denoted $\beta 1$, with $\mu = 8.8$), and non-magnetic (denoted $\beta\infty$, with $\mu = \infty$). These simulations can be thought of as representing regions of size $L = 4$ pc, with a mean number density $n_0 = 500$ cm$^{-3}$, a turbulent velocity dispersion of 2 km s$^{-1}$, and a sound speed $c_s = 0.2$ km s$^{-1}$, with mean field strengths of 46, 14.5, 4.5 and 0 $\mu$G, respectively.

Figure 1 shows the evolution of the global density maximum for all four runs, with the time axis shown in units of the sound crossing time $\tau_s \equiv L/c_s = 20$ Myr (lower axis) and of the global free-fall time $\tau_{fg} \equiv L_J/c_s = 5$ Myr (upper axis). It is readily seen that the subcritical run $\beta.01$ does not produce very large density enhancements, with the global density maximum at any given time being $\sim 30 n_0$, and never exceeding $100 n_0$. These values are too low, and the transients are too short ($< 1$ Myr), for ambipolar diffusion to operate and reduce the magnetic flux under canonical estimates of the ambipolar diffusion time scale (see, e.g., McKee et al. 1993). Note also that this occurs even though this run is very close to global criticality, and thus the production of gravitationally-bound cores in subcritical environments appears to be highly unlikely even for nearly critical boxes. Finally, note that the densities encountered in this run are also safely below the "Jeans criterion" of Truelove et al. (1997) ($n < 256n_0$ for our resolution of $256^3$ grid zones) and the extension of it proposed by Heitsch, Mac Low & Klessen (2001) ($n < 115n_0$) to ensure that numerical diffusion does not significantly damp MHD waves within the cores, and so our result is robust. Note, moreover, that these criteria may be excessive for the problem at hand, as it was shown by Heitsch et al. (2001) that the magnetic field can only prevent collapse if it provides *magnetostatic* support, rather than wave-pressure support. So our main resolution concern is to avoid magnetic flux loss, not damping of MHD waves. In turn, the Truelove et al. (1997) criterion is only defined in order to prevent artificial fragmentation of collapsing structures, but here we are not concerned with the internal structure of the cores as they collapse; rather, we are just interested in whether collapse occurs or not. Thus, a more appropriate criterion may be that the internal mass-to-flux ratio of the cores does not exceed that of the numerical box, or of its parent structure, as discussed above (i.e., that the mass-to-flux ratio does not increase inwards of a density structure).

In contrast, the supercritical and nonmagnetic runs rapidly develop densities approaching $10^4 n_0$, which correspond to collapsed, unresolved objects. These densities occur at $\sim 1/2\tau_{\rm fg}$ in the magnetic runs, and at $\sim 1/5\tau_{\rm fg}$ in the non-magnetic one. However, inspection of animations of the simulations (available at `http://www.astrosmo.unam.mx/~e.vazquez/turbulence_HP/movies/VKSB04.html`, or in Vázquez-Semadeni et al. 2004) shows that the typical time spans from the beginning of the turbulent compression to the completion of collapse are $\sim$ 1–1.5 *local* (i.e., at the mean density of the core) free-fall times ($\tau_{\rm fc}$), or, equivalently, $\sim$ 0.1–0.15 $\tau_{\rm fg}$.

Measurement of the Jeans number and mass-to-flux ratio of the cores as they are formed and evolve towards collapse sheds light on how the process occurs. In Table 1, we present these parameters, together with other relevant data, for the first collapsed object that forms in run $\beta$.1. Other cores have similar histories. The animation shows that this object forms out of a larger clump initially containing two cores, which ultimately merge to form the collapsed object (see also Figure 2). Table 1 thus gives the data for the structures defined out to a threshold density level $n_{\rm t}$ from the local maxima at three different times during the evolution of the system. The

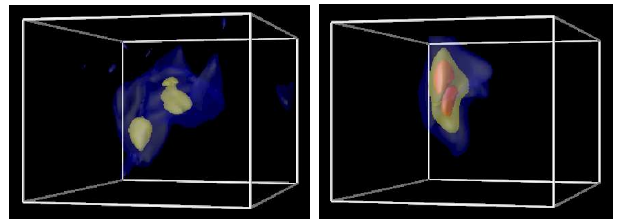

Fig. 2. Iso-density surface 3D map of the clump-core (cores 1 and 2) system appearing at early times in run $\beta$.1, detailed in Table 1. The times shown are $t = 0.06\tau_{\rm s}$ (*left*) and $t = 0.08\tau_{\rm s}$ (*right*). The iso-density surfaces are at $n = 10n_0$ (blue), $n = 40n_0$ (yellow) and $n = 100n_0$ (red). The latter does not exist at $t = 0.06\tau_{\rm s}$.

times are in units of the box sound-crossing time. At the time $t = 0.06\tau_{\rm s}$, the threshold $n_{\rm t} = 40n_0$ resolves the two cores, but at the two later ones only one core is seen above this threshold (see Figure 2).

From Table 1 it is seen that the parent clump (defined by setting $n_{\rm t} = 10n_0$) is already super-Jeans and supercritical at $t = 0.06\tau_{\rm s}$, but the daughter cores (defined by $n_{\rm t} = 40n_0$) are still sub-Jeans and subcritical. Both the mean and peak densities (respectively $\bar{n}$ and $n_{\rm p}$) within the parent and daughter structures are safely below even the most stringent condition of $n < 115n_0$ for avoidance of MHD wave damping by numerical diffusion, and so the supercritical nature of the parent clump is a robust physical result, and the clump cannot be supported by the magnetic field. Of course, there remains the possibility of turbulent support, but since the clump itself was formed by a turbulent compression, the compressive energy clearly overwhelms the internal, random, supporting one, and in fact is the mechanism that drives the clump into becoming super-Jeans and supercritical. In any case, a detailed analysis of the virial balance of the clump/core system and the role of the velocity field, to be presented elsewhere, is necessary, but here we have shown that the magnetic field is insufficient for supporting the parent clump, even though its densest regions (the daughter cores) are initially subcritical and sub-Jeans. At the later times $t = 0.08\tau_{\rm s}$ and $t = 0.1\tau_{\rm s}$, the single core defined by $n_{\rm t} = 40$ also has become super-Jeans and supercritical, as expected for the generalized collapse of the parent clump. Although finally at time $t = 0.1\tau_{\rm s}$ numerical diffusion is clearly important ($\mu_{\rm c} > \mu$), this is seen to occur *after* the onset of the clump's collapse, which began while the core/clump system was still well resolved.

A final observation that here we only mention briefly (see Vázquez-Semadeni et al. 2004 for a full

TABLE 1

PARAMETERS OF CLUMPS AND CORES IN RUN $\beta$.1.

| Core name | Time[a] | $n_t$[b] | $\bar{n}$[c] | $n_p$[d] | $R_c/L$[e] | $J_c$[f] | $\mu_c$[g] |
|---|---|---|---|---|---|---|---|
| Parent clump | 0.06 | 10 | 19.0 | 83.0 | 0.071 | 1.27 | 1.73 |
| Core 1 | 0.06 | 40 | 51.1 | 83.0 | 0.018 | 0.53 | 0.90 |
| Core 2 | 0.06 | 40 | 44.4 | 56.0 | 0.020 | 0.54 | 0.86 |
| Single core | 0.08 | 40 | 78.5 | 337. | 0.041 | 1.45 | 2.09 |
| Single core | 0.10 | 40 | 329. | $5.07 \times 10^3$ | 0.031 | 2.28 | 4.66 |

[a]Time of observation of structure, in units of $\tau_s$.

[b]Threshold density for clump/core identification.

[c]Mean density of clump/core.

[d]Maximum density within clump/core.

[e]Clump/core radius in units of the computational box size $L$.

[f]Ratio of core's radius to its Jeans length.

[g]Mean mass-to-flux ratio within clump/core in units of the critical value (compare to simulation value of 2.8).



discussion) is that in the strongly supercritical run $\beta$1, two cores with slightly longer durations ($\sim 5\tau_{\rm fc}$) are formed, but in both cases they end up re-dispersing, rather than collapsing. This is in agreement with the simple argument that re-expansion should take longer times than compression or collapse, because in that case self-gravity acts as *retarding* agent against the re-expansion.

## 4. CONCLUSIONS

In this contribution, we have presented a discussion and numerical simulations of the formation, nature, and lifetimes of dense cores in magnetized clouds. We argued that the mass-to-flux ratio of a cloud puts an upper bound to that of any clump or core within it, and so the only way to form supercritical cores is within supercritical clouds (neglecting ambipolar diffusion). Moreover, numerical simulations of marginally subcritical clouds show that no gravitationally bound cores form in this case, while in supercritical clouds the gravitationally bound cores that form occur inside clumps that are supercritical, and rapidly become supercritical themselves and collapse, in timescales that do not exceed twice their local free-fall time $\tau_{\rm fc}$. We also showed that the mass-to-flux ratio of structures defined through a density threshold (as would be the case of cores observed in a single molecular line, which requires the density to be larger than a certain value in order to be excited) does not remain constant, because the core is continuously connected to its parent structure, from which it can accrete mass. Our results support the notion that clumps and cores are out-of-equilibrium, transient structures, and that a class of "failed" cores should exist, that will not form stars.

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