FORMATION AND COLLAPSE OF QUIESCENT CLOUD CORES INDUCED BY DYNAMIC COMPRESSIONS

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ABSTRACT

We present numerical hydrodynamical simulations of the formation, evolution and gravitational collapse of isothermal molecular cloud cores induced by generic turbulent compressions in spherical geometry. A compressive wave is set up in a constant sub-Jeans density distribution of radius \( r = 1 \) pc. As the wave travels through the simulation grid, a shock-bounded layer is formed. The inner shock of this layer reaches and bounces off the center, leaving behind a central core with an initial almost uniform density distribution, surrounded by an envelope consisting of the material in the shock-bounded shell, with a power-law density profile with index close to \(-2\) even in non-collapsing cases. The central core and the envelope are separated by a weak shock. The resulting density structure resembles a quiescent core of radius \( \lesssim 0.1 \) pc, with a Bonnor-Ebert-like (BE-like) profile, although it has significant dynamical differences: it is initially non-self-gravitating and confined by the ram pressure of the infalling material, and consequently, growing continuously in mass and size. With the appropriate parameters, the core mass eventually reaches an effective Jeans mass, at which time the core begins to collapse and eventually a singularity is formed. The time delay caused by the core buildup generates a population of pre-stellar cores with a Bonnor-Ebert-like profile that are not in hydrostatic equilibrium and might or might not experience gravitational collapse, which is consistent with the large observed frequency of cores with BE-like profiles. In our collapsing simulation a time \( \sim 0.5 \) Myr elapses between the formation of the core and the time at which it becomes gravitationally unstable, and another \( \sim 0.5 \) Myr are necessary for it to complete the collapse.

Subject headings: ISM: clouds — ISM: evolution — ISM: structure — stars: formation — turbulence

1. INTRODUCCION

The process by which a gas parcel ("core") within a molecular cloud (MC) initiates a collapse leading to the formation of a star or group of stars remains loosely understood, in particular the details of its dynamical evolution. Observations indicate that "prestellar" molecular cloud cores (i.e., those that do not yet contain a protostellar object, but that appear to be on route to forming it) have a density structure that resembles Bonnor-Ebert (BE) profiles (Ebert 1955; Bonnor 1956), being nearly flat in their central regions, while approaching the singular isothermal sphere (SIS) profile \( n(r) \propto r^{-2} \) at large radii. "Stellar" cores (those already containing a Class 0 or Class I protostellar object), on the other hand, appear to have density profiles closer to that of the SIS throughout their volume (e.g., Alves, Lada & Lada 2001; Caselli et al. 2002; Kirk et al. 2005; Lee et al. 2007) (see also the reviews by Lada et al. 2007; di Francesco et al. 2007; Ward-Thompson et al. 2007, and references therein).

The line profiles and spatial distribution of molecular-line observations provide further clues to the dynamics. For example, based on observations of CS(3-2), CS(2-1), DCO\(^+\)(2-1) and \(N_2H^+\)(1-0), Lee et al. (2004) found a moderate fraction of prestellar cores (18 out of 70 in their Table 2) showing clear evidence of subsonic inward radial motions, at velocities \( v \lesssim 0.07 \) km s\(^{-1}\). Moreover, studies of individual starless cores have suggested that the radial velocity does not increase appreciably towards the center (Tafalla et al. 1998; Williams et al. 1995; Tafalla et al. 2004; Lee et al. 2007). Those inward motions frequently extend to long enough distances from the cores’ centers (a few tenths of a parsec) that they seem inconsistent with the “inside-out” collapse model of Shu (1977), since a central protostar should have had time to form by the time the rarefaction wave reaches those distances (di Francesco et al. 2007, and references therein).

A large number of theoretical studies have investigated the collapse process starting from a variety of initial and boundary conditions, both analytically, through similarity solutions, as well as numerically (e.g., Larson 1969; Penston 1969; Shu 1977; Hunter 1977; Foster & Chevalier 1993; Hennebelle et al. 2003). All of these studies have considered the collapse of a fixed mass of gas, either through the usage of a hot, tenuous confining medium that pressure-confines the core while adding no weight to it, or through fixed boundaries. Moreover, most of these studies used static initial configurations, either with uniform density or with BE hydrostatic equilibrium profiles.

On the other hand, MCs are thought to be supersonically turbulent, since they exhibit supersonic linewidths (Zuckerman & Palmer 1973), and MC cores, as well as their parent MCs themselves, have been suggested to be turbulent density fluctuations within their environments (Ballesteros-Paredes et al. 1999), being produced by effectively supersonic compressions. Hunter & Fleck (1982) showed that the effective Jeans mass of a fluid...
parcell subject to an external compressive velocity field is significantly decreased with respect to its normal static value. Furthermore, Vázquez-Semadeni et al. (2005) have recently pointed out that, if MCs are isothermal, then the hot, tenuous medium necessary to confine and stabilize a hydrostatic equilibrium configuration is not available, and the equilibrium state is then expected to be unstable in general. This leads naturally to the question of whether hydrostatic equilibrium configurations can be produced in such turbulent conditions, and if so, how do they arrive at that state. Otherwise, if the entire process is dynamic, one can ask what is the density and velocity structure of the cores at the time they engage into collapse and, if different from the initial conditions normally assumed, what effects does it have on the evolution. Moreover, if the core is formed and induced to collapse by a compressive wave, then in general there is an inflow that builds up the core dynamically, and the mass that ends up collapsing is not previously determined by the initial conditions, but rather is determined “on the spot” depending on the local instantaneous conditions. The studies of collapse mentioned above cannot answer these questions, since they already assume gravitationally unstable structures, and initial hydrostatic equilibrium configurations, so that all of the mass is involved in the collapse.

The study that comes closest to these goals is that by Hennebelle et al. (2003), who investigated the effect of increasing in the pressure external $P_{\text{ext}}$ to an initially stable BE sphere. They noted that the resulting configurations better match the observations because the density profile is flat at the center, and the prestellar phase is characterized by subsonic inwards velocities at the outskirts, and nearly zero velocity at the inner parts. However, having a hot confining medium outside and an initial hydrostatic profile, this study still could not capture the core formation part of the evolution, and predetermined the mass that collapses from the initial conditions. Also, it did not consider the possibility of a transient compression and thus of a failure to collapse.

Motivated by these questions, in this paper we then present numerical simulations of hydrodynamic collapse in spherical coordinates triggered by an external transient compression in otherwise gravitationally stable regions, with the purpose of investigating the evolution of the density and velocity profiles in both collapsing and re-expanding (“failed”) cases, the timescales required for a core to be assembled and then collapse or redisperse, and the mechanism by which a certain fraction of the mass is gravitationally “captured” to then proceed to collapse.

In particular, the timescale issue is relevant because it is often thought that the prestellar lifetimes of the cores in the turbulent scenario of star formation are of the order of one core’s free-fall time $\tau_{ff}$. However, it has been shown by Vázquez-Semadeni et al. (2003) and Galván-Madrid et al. (2007) that even in highly dynamical, driven-turbulence simulations, the lifetimes are a few to several times $\tau_{ff}$. It is important then to investigate the detailed evolution of cores formed by turbulent compressions, to understand the reason for those observed timescales.

The plan of the paper is as follows. In §2 we present the numerical setup of the problem, and in §3 we present the results of two fiducial cases of core evolution, one collapsing and one rebounding. In §4 we then discuss the implications of our results, and compare with existing observational and theoretical work.

2. THE NUMERICAL SETUP

For this work, we consider an idealized spherical cloud that experiences a compression wave. By considering a uniform density distribution and allowing the system to dynamically choose the amount of mass involved in the collapse, we avoid some of the restrictions that previous work has imposed on the evolution. Nevertheless, we still adopt a spherical geometry; this enforces the central position of the collapsing object, and restricts the nature of the compressible wave to spherical shells. A more general collapse without this geometrical constraint is left for future work.

The hydrodynamic evolution of this setup was solved using ZEUS [Stone & Norman 1992], a finite difference, time explicit, operator split, hydrodynamic code. The calculations were performed on a 1D spherical grid, with the domain spanning the $0 < r < 1 \text{ pc}$ range with 1000 grid points spaced such that $\delta r_{i+1}/\delta r_i = 1.005$. This yields a spatial resolution of $\approx 3 \times 10^{-5} \text{ pc}$ at the inner boundary, and $\approx 5 \times 10^{-3} \text{ pc}$ at the outer boundary. (Selected simulations were performed with a much higher resolution of 4000 grid points and no significant differences were observed.) The boundary conditions are reflecting at $r = 0$ and outflow at $r = 1 \text{ pc}$. No confining agents are used whatsoever (closed boundary nor hot tenuous medium), implying that mass can freely leave the system, although it cannot enter. The absence of a confining agent attempts to emulate the situation of a density enhancement immersed in a much more extended medium at the same temperature.

All simulations started with a constant density distribution, an isothermal equation of state, and a temperature $T = 11.4 \text{ K}$ which, with a mean particle mass $\mu = 2.36m_H$, yields an isothermal sound speed $c_s = 0.2 \text{ km s}^{-1}$. This setup was perturbed by a compressive velocity pulse given by the relation

$$v(r) = \begin{cases} 0, & r < r_0 - dr_0; \\ -v_0 \sin \left(\frac{\pi}{2} \frac{r - r_0}{dr_0}\right), & r_0 - dr_0 < r < r_0 + dr_0; \\ -v_0 \sin \left(\frac{\pi}{2} \frac{r - r_0}{dr_0}\right), & r_0 + dr_0 < r; \end{cases}$$

where $v_0$ and $r_0$ are parameters of the simulation, $dr_0 = 0.1 \text{ pc}$, $r_1 = [r_{\text{max}} + (r_0 + dr_0)]/2$, and $dr_2 = [r_{\text{max}} - (r_0 + dr_0)]/2$, with $r_{\text{max}} = 1 \text{ pc}$. A simple self-gravity module was also added to the code.

This approach continues along the lines of simple, basic models that have explored the gravitational collapse of MC cores, since Larson (1969) and Penston (1969a,b), through Hennebelle et al. (2003), which have been extended to include an initial velocity impulse, intended to mimic the random compressive motions expected in a turbulent medium. Nevertheless, the one-dimensional
nature of the model, together with the adopted spherical geometry, makes this setup somewhat unphysical as this compressive wave is spherical, while turbulent compressions are most likely to be planar, although two- or three-dimensional compressions may occur at the intersections of sheets formed by planar compressions. Also, “turbulent” support in this model is present only as purely divergent motion, with no rotational component. A more appropriate way of modeling the core formation process would be to perform full 3D numerical simulations, via random compressions of finite cross-section generated by bulk motions of the gas, similarly to what has been done for the diffuse medium by Vázquez-Semadeni et al. (2007). We intend to pursue this in the near future.

Another limitation introduced by the adopted geometry is the large mass of the collapsed core resulting from our simulations (cf. 3.2). In a more realistic simulation, without the geometrical and symmetry restrictions, the collapsing system would probably undergo fragmentation. Therefore, we see the collapsed objects generated in these simulations not as a single star, but as the precursor of a small cluster.

3. THE SIMULATIONS

3.1. Spontaneous collapse

In order to study the effect of velocity fields in inducing the collapse of molecular cloud cores, we first need to determine when they can collapse under the influence of their self-gravity alone. Because of the adopted spherical geometry (the usual Jeans analysis is applicable to sinusoidal perturbations in plane parallel geometry), the critical density $\rho_c$ and mass (which we refer to as the effective Jeans mass) at which the core collapses may differ slightly from the standard Jeans values, and so we determine them here numerically. We let $t_0 = 0$ and let the simulation run for 10 Myr with a series of different initial densities.

As the simulations are started, self-gravity causes the cloud to begin contracting, increasing its mean density (see fig. 1). At some point, the pressure in the inner parts stops this process and the collapse is reversed (the cloud “bounces” momentarily). If the cloud’s mass is large enough, self-gravity takes over again, and the expansion is reversed again and the cloud collapses; otherwise, the expansion continues until the simulation ends. It is found that an initial density value of 160 cm$^{-3}$ yields a collapsing core, while a 2% lower density does not; therefor, we take the critical density as $\rho_c = 160$ cm$^{-3}$. At this density, the mass in our numerical box (of radius $R = 1$ pc) is $M_{\text{box}}(\rho_c) = 39.1 M_\odot$. For comparison, the mean density for which the standard Jeans length equals the diameter of the numerical domain (2 pc) is $\bar{\rho} = \rho_1 \equiv \pi \bar{\rho}^2 / G L_1^2 = 125$ cm$^{-3}$.

In the light of this result, we define the effective Jeans mass as the spherical Jeans mass (i.e., a sphere with diameter equal to the Jeans length at mean density $\bar{\rho}$) times a fudge factor $A$ so that the product equals the box’s mass at the empirical critical density:

$$M_{\text{eff}} = A \frac{4\pi \rho_c}{3} \left( \frac{L_1}{2} \right)^3$$

where $k_B$ is the Boltzmann’s constant, $T$ is the temperature, $\mu = 2.36$ $m_H$ is mean particle mass, and $G$ is the gravitational constant. By setting $M_{\text{eff}} = M_{\text{box}}$, we obtain $A = 1.45$. For comparison, the standard Jeans mass at $\rho_c$ is $M_J = 27.0 M_\odot$, and the BE mass (Ebert 1955; Bonnor 1956) is $M_{\text{BE}} = 1.18 \rho_0^3 / (G^3 \rho_c)^{1/2} = 10.0 M_\odot$.

3.2. Cores formed by ram-pressure

Although a large number of simulations were performed, our discussion will focus on two of them, respectively representative of non-collapsing and collapsing cases. We shall call S1 the simulation with the initial velocity impulse at $r_0 = 0.33$ pc, while simulation S2 places the impulse at $r_0 = 0.67$ pc. Both simulations have the same velocity amplitude ($v_0 = 0.4$ km s$^{-1} = 2 c_s$) and sub-critical initial density (112.7 cm$^{-3}$ $\approx 0.7 \rho_c$), meaning that in the absence of compressive motions, both simulations would simply expand away.

The evolution of simulation S1 is shown in Figure 2. This figure respectively shows, as a function of radius, the density, the logarithmic slope of the density radial profile, the velocity, and the core’s mass (solid line) and Jeans mass (dashed line) inside the radius, in the four rows from top to bottom at selected times (left to right columns). Shortly after the starting time ($t \approx 0.28$ Myr), a shock-bounded shell appears in the inner side of the initial velocity pulse, at $\log r \approx -0.7$ ($r \approx 0.2$ pc). The inner shock propagates inward, carrying a large amount of mass with it (fig. 2b). When the inner shock reaches the center of the cloud ($t \approx 0.77$ Myr), geometrical focusing dramatically increases the internal density, lowering the effective Jeans mass of the inner parts of the cloud (c). As the shock bounces off the center and expands outwards, the shocked gas behind it is left at uniform density and at essentially zero velocity; that is, a quiescent core is formed inside the shock-bounded shell (d). This result provides the physical basis behind the claims that cores are stagnation points of the turbulent flow in MCs (Klessen et al. 2004).

Meanwhile, the gas from the shock-bounded shell continues to fall in, being incorporated into the quiescent core as it passes through the inner shock, which is now moving outwards. This increases the mass of the core, although the density is somewhat lowered again after the strong transient produced by the convergence of the shock at the center. As a result, the Jeans mass increases in the innermost parts of the core, and decreases close to the shock-bounded layer and within it. As the core acquires more mass, its density profile starts deviating from being uniform, and approaching that of a truncated self-gravitating sphere. Finally, in this simulation, the mass of the inner core never becomes equal to $M_{\text{eff}}$ at any radius, and the uniform-density core continues to expand indefinitely, developing positive velocities at the outermost regions first (e).

In simulation S2, the early evolution is quite similar to that of S1. At $t \approx 1.5$ Myr, the inner shock of the layer bounces off the center of the core (fig. 3a) and begins traveling outwards. But then, some 0.5 Myr later ($t \approx 2.0$ Myr), the amount of mass in the core finally becomes equal to $M_{\text{eff}}$ at $r \approx 0.07$ pc, and from that...
FIG. 1.— Spontaneous collapse of the cloud without velocity impulse. Left: when started with a constant density $n = 175.70 \text{cm}^{-3}$, the central region of the cloud undergoes gravitational collapse after a small bounce off the center. Right: when started with a constant density $n = 112.72 \text{cm}^{-3}$, the cloud bounces off its center and expands until it disperses.

momenton, collapse ensues, culminating with the formation of a singularity at $t \approx 2.6 \text{ Myr}$ (e). It is interesting that at $t \approx 2.0 \text{ Myr}$, the mean density in the quiescent core is $n \approx 2.85 \times 10^4 \text{ cm}^{-3}$, implying a free-fall time $\tau_f \approx 0.2 \text{ Myr}$, less than half the time the actual collapse takes. There are several reasons possibly responsible for the discrepancy with the observed collapse time of 0.6 Myr (from $t = 2 \text{ Myr}$ to $t = 2.6 \text{ Myr}$). For example, it was already noted by Larson (1969, Appendix C) that the actual collapse time lasts nearly 1.5 the free-fall time, because the pressure is never completely negligible. The remaining difference (a factor of $\sim 70\%$), is probably due to the imprecisions introduced by considering the mean density rather than the detailed radial distribution, the fact that the core is increasing its mass, so that the instability sets in at an undetermined radius, and the non-negligible mass of the envelope.

A very interesting element of both simulations is the fact that the density structure of the core resembles a BE sphere while the shock front is traveling outwards (column d in figs. 2 and 3), when the innermost parts of the core have a nearly constant density and the shock-bounded layer has an $n \sim r^{-2}$ distribution, even though it is not in equilibrium. After the formation of the singularity at the center, the $r^{-2}$ density profile extends throughout the core, similarly to a SIS profile (fig. 3).

4. DISCUSSION

FIG. 2.— Evolution of simulation S1. Each row shows the evolution (down from the top) of density ($n$), logarithmic density slope ($d \log n/d \log r$), velocity ($v_r$), mass internal to radius $r$ ($M(r)$, solid line) and effective Jeans mass ($M_{J,\text{eff}}$, dashed line) at 0.000 (column a), 0.625 (b), 0.775 (c), 0.925 (d), and 1.500 Myr (e). Arrows show the direction of motion of the shocks. [See http://www.astrosmo.unam.mx/~g.gomez/publica/f2.mpg for an mpeg animation of this figure]
4.1. Implications

The evolution of simulation S2 has a number of interesting important implications, which we now discuss.

First, a compressive wave (or a negative-divergence velocity field) does not directly induce the collapse of an initially sub-Jeans core. The collapse happens only after the resulting shock front rebounds from the center, begins to move outwards, and incorporates enough mass into the central core that a “traditional” Jeans criterion \[ M(r) > M_{\text{Jeans}} \] is satisfied there. Since the material behind the shock is left at zero velocity, no turbulent support is ever at play there. That is, the collapse does not occur because turbulence is dissipated in the core, as it is often believed, but rather, because the growing core eventually reaches the effective Jeans mass. Moreover, as the shock continues to move outwards, the size of the region acquiring the effective Jeans mass increases, so that the determination of the mass that eventually is incorporated into the collapse happens “on the spot” in a highly fortuitous manner.

Second, a near-\(r^{-2}\) density profile is established in the envelope around the central core, even in cases that do not collapse. However, in our case, this is not the consequence of subsonic initial conditions, as proposed by Shu (1977), but rather of the fact that the envelope consists of shocked gas (the gas contained in the shock-bounded shell; see Figs. 2 and 3). Shu (1977) proposed subsonic initial conditions so that different parts of the cloud could communicate acoustically with each other and thus develop detailed mechanical balance. Instead, in our simulations, the initial conditions are supersonic, but the gas in the envelope consists of the gas within the shock-bounded shell, which has been shocked and thermalized, thus brought into acoustic contact. We see that it is this gas that later develops the \(r^{-2}\) density profile. Thus, subsonic initial conditions are not necessary.

Third, the velocity profile after the central core has formed has nearly zero velocity in the central (quiescent) core, and an infalling velocity field in the outer envelope (Figs. 2f and 3f). The core and the envelope are separated by the outwards-traveling shock, which is, however, very mild, with a Mach number of order unity.

Fourth, there is a time delay between the formation of the core and its gravitational collapse. The quiescent core grows from the center as the shock moves outwards incorporating mass into the central shocked region. This process cannot happen instantaneously, but rather requires a finite time until the core’s mass equals the effective Jeans mass. In our simulations, roughly 1 Myr spans from the moment of central core formation to the development of a singularity at the center, with roughly half of it being spent without any tendency to collapse. This time delay naturally generates a population of starless cores with BE-like profiles, with a flat central density distribution and a near-\(r^{-2}\) envelope.

Fifth, it is important to remark that even though our quiescent cores are morphologically similar to BE spheres, they are dynamically very different: they are not self-gravitating hydrostatic structures confined by the thermal pressure of a hot, tenuous medium, but instead they are initially non-self-gravitating, confined by the ram-pressure of the inflowing gas from the envelope, and growing in size and mass accordingly, until they become self-gravitating, at which point they engage into collapse.

Sixth, and finally, it appears that the whole evolution is not very amenable to a similarity solution because: a) the initial velocity pulse is finite, so that the external flow is not rescalable. b) The inner shock bounding the shock-bounded shell hits the center and bounces back towards the exterior. c) The central core gradually increases its self-gravity and eventually may become gravitationally unstable, a process that continuously transforms the core’s density profile from uniform to being BE-like, first stable and then unstable.

4.2. Comparison with previous work

It is interesting to compare the results of our numerical simulations to those of previous studies. The main
difference is that our simulations have investigated the formation of the cores in addition to their subsequent collapse, in order to study whether BE-like structures can be produced out of supersonic turbulent compressions in isothermal molecular clouds. Thus, in particular, our study sheds light on the realizability of the initial conditions used by previous works.

Our results suggest that in fully isothermal molecular clouds (i.e., without a warm, tenuous interclump medium that can stabilize a density enhancement), collapsing structures formed by random turbulent compressions in the medium morphologically resemble BE spheres through a large fraction of their evolution, because they consist of a central core and an infalling envelope, which at all times after the formation of the central core has a density profile with a slope close to $-2$. This extends the results that plane-of-sky angular averaging and line-of-sight averaging cause the observed density profiles to be smoother that the actual ones (Ballesteros-Paredes et al. 2003; Hartmann 2004). At later times, shortly before and after the onset of gravitational collapse of the core, the latter also develops a density profile close to that of a BE sphere, which connects with that of the envelope. This means that, at the onset of gravitational collapse, our simulations favor initial conditions such as those used by Foster & Chevalier (1993), albeit with the added ingredient of a continuous accretion at the bounding shock.

Some authors have already studied spherically symmetric flows with shocks in the context of protostar formation using similarity methods (e.g., Shen & Lou 2004; Lou & Gao 2006; Lou & Wang 2006). Similarity studies are extremely useful in extracting the underlying asymptotic behavior of real flows. Therefore, it is important to compare our numerical solutions with existing similarity solutions of self-gravitating clouds in the presence of shocks, in particular those of Shen & Lou (2004), hereafter SL04), whose study most resembles our numerical setup. These authors presented two possible classes of self-similar shocked flow in the context of the dynamical evolution of protostars, depending on the asymptotic behavior of the solutions near the center of cloud. Their Class I solutions had negative (inflow) velocities ($\propto -r^{1/2}$), a density profile $\rho \propto r^{-3/2}$, and finite mass as asymptotic limits at $r \to 0$, while their Class II had positive (expansion) velocity ($\propto r$), constant finite density and vanishing mass ($\propto r^3$) as the asymptotic behavior in the same limit. In both classes, an outward-moving shock separates a collapsing (or expanding) inner part and an accreting outer part. None of these behaviors are seen in our simulations at any time. Their Class II is similar to our solutions during the core-growth stage, in that it has a uniform central density and an accreting outer part, which has a counterpart in the infalling shock-bounded layer in our models. However, in our system the central core is neither expanding nor contracting, but rather it is at rest. This difference is most likely a consequence of our cores being non-self-gravitating at the early stages of their evolution. That is, unlike the SL04 solution, where self-gravity is important at all radii and at all times, in our simulations the relative importance of self-gravity increases secularly with time, going from being zero at the time of core formation to being dominant at the time when gravitational instability sets in.

Another recent study that is closely related to ours is that by Hennebelle et al. (2003), who numerically investigated the effect of increasing the pressure external $P_{\text{ext}}$ to an initially stable BE sphere. These authors found that slow rates of increase of $P_{\text{ext}}$ cause the sphere to approach instability quasi-statically, but higher rates of increase produced a compressive wave that triggers an outside-in collapse. It is noteworthy, however, that they do not report the bounce of the compressive wave from the center that we find. This is most probably because, in their case, the wave compresses a previously-existing core that is in a (fragile) stable hydrostatic equilibrium state, and so the role of the wave is to directly trigger the collapse. Instead, in our case, the compressive wave forms the core, and adds mass to it until it becomes gravitationally unstable and proceeds to collapse. Moreover, in the case of Hennebelle et al. (2003), the mass of the core was fixed, being bounded by a hot, tenuous medium, while in our case, the fraction of the mass that is driven to collapse is determined “in real time” by the interplay between the accreting gas and the outgoing shock wave, and moreover the mass that becomes gravitationally unstable increases with time, so the collapse proceeds “inside out” but over an intermediate range of radii. Thus, we see that the choice of equilibrium or out-of-equilibrium initial conditions and continuous or discontinuous boundary conditions leads to very different patterns of evolution. Which model applies best to actual turbulent molecular clouds probably depends on whether they consist of a single, nearly isothermal molecular phase (our model), or of a mixture of colder, denser molecular cloudlets immersed in a more tenuous and warmer atomic medium (Hennebelle & Inutsuka 2000). Extensive theoretical and observational work, focusing especially on the velocity structure of the cores, is needed to decide on this issue. The recent results of Lee et al. (2007), indicating the presence of a sharp infall velocity increase at $\sim 0.03$ pc from the centers of the starless cores L694-2 and L1197, would seem to favor the dynamical scenario for the formation of the cores.

5. SUMMARY AND CONCLUSIONS

In this paper we have performed a numerical study of the formation of dense cores by dynamical compressions in isothermal, non-magnetized media, using simple one-dimensional calculations in spherical geometry. Our results show that cores assembled by this process consists of a central, quiescent core with density $10^5$ cm$^{-3}$ that grows in mass and size as it accretes mass from a surrounding envelope, which early in the evolution develops a radial density profile with a logarithmic slope approaching $\sim -1.75$. The quiescent core and the envelope are separated by a weak shock with Mach number just above unity, and the accretion from the envelope provides ram-pressure that confines the central quiescent core. As the central core increases its mass, it passes first through a non-self-gravitating, uniform-density stage, and, as it becomes increasingly self-gravitating, it evolves into a “pseudo BE-sphere” stage, first stable and finally unstable, at which point collapse ensues. This process requires a relatively long time to complete, taking $\sim 0.5$ Myr from the first appearance of the central core to the time it becomes gravitationally unstable, and another $\sim 0.5$ Myr.
for the collapse to produce a singularity at the center.

At all times since the appearance of the central quiescent core, the combined density structure of the core+envelope system resembles a BE sphere, as it is flattened at the center, and has a near-power-law envelope with slope close to $-2$. Thus, the high observed frequency of BE-like profiles (e.g. di Francesco et al. 2007; Lada et al. 2007) is naturally accommodated in this scenario of dynamic assembly of MC cores. However, the structures are not classical BE spheres, because they are confined by ram-, rather than by thermal pressure, and are consequently accreting mass and growing in mass, size, and self-gravitating energy, in a process analogous to that described for the formation of giant MCs by Vázquez-Semadeni et al. (2007). In both cases, there is a secular evolution characterized by the mass increase of the cloud or core, that proceeds out of equilibrium from beginning (first appearance of high-density gas) to end (appearance of central collapsed objects).

The velocity structure of the cores thus formed appears consistent with recent radiative transfer models for the structure of cores L694-2 and L1197 presented by Lee et al. (2007), which exhibit a nearly zero central velocity and a sharp rise at radii $\sim 0.03$ pc. We plan to carry out a radiative transfer study of the density and velocity structures produced by our models in the near future, in order to perform detailed comparisons with observational studies based on multi-tracer studies (e.g. Lee et al. 2004) as well as on line-profile mapping of prestellar cores (e.g., Tafalla et al. 1998, 2004; Lee et al. 1999, 2007).

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For the structure of cores L694-2 and L1197 presented by Lee et al. (2007), which exhibit a nearly zero central velocity and a sharp rise at radii $\sim 0.03$ pc. We plan to carry out a radiative transfer study of the density and velocity structures produced by our models in the near future, in order to perform detailed comparisons with observational studies based on multi-tracer studies (e.g. Lee et al. 2004) as well as on line-profile mapping of prestellar cores (e.g., Tafalla et al. 1998, 2004; Lee et al. 1999, 2007).

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