Abstract. We present preliminary numerical evidence that the physical conditions in high-mass star forming regions can arise from global gravitational infall, with the velocity dispersions being caused primarily by infall motions rather than random turbulence. To this end, we study the clumps and cores appearing in the region of central collapse in a numerical simulation of the formation, evolution, and subsequent collapse of a dense cloud out of a transonic compression in the diffuse atomic ISM. The clumps have sizes $\sim 1$ pc, masses of several hundred $M_\odot$, and three-dimensional velocity dispersions $\sim 3$ km s$^{-1}$, in agreement with typical observed values for such structures. The clumps break down into massive cores of sizes $\sim 0.1$ pc, densities $\sim 10^5$, masses 2-300 $M_\odot$, with distributions of these quantities that peak at the same values as the massive core sample in a recent survey of the Cygnus X molecular cloud complex. Although preliminary, these results suggest that high-mass star forming clumps may be in a state of global gravitational collapse rather than in equilibrium supported by strong turbulence.

1. Introduction

High-mass star forming regions are characterized by more extreme physical conditions than their low-mass counterparts (e.g., Garay & Lizano 1999; Kurtz et al. 2000; Beuther et al. 2007), having “clumps” of sizes 0.2–0.5 pc, mean densities $n \sim 10^5$ cm$^{-3}$, masses between 100 and 1000 $M_\odot$, and velocity dispersions ranging between 1.5 and 4 km s$^{-1}$. In turn, these clumps break down into even denser “cores” that are believed to be the immediate precursors of single or gravitationally bound multiple massive protostars. The high velocity dispersions of these clumps are generally interpreted as strong turbulence that manages to support the clumps against gravity (e.g., Garay & Lizano 1999; McKee & Tan 2003). However, the notion of “turbulent support” is difficult to maintain at the scales of these cores. Turbulence is a flow regime in which the largest velocity differences are associated with the largest separations (e.g., Frisch 1995), and moreover in the case of supersonic turbulence the clumps are expected to be formed by...
large-scale compressive motions, so that the turbulence is likely to have a strong compressive component (Hunter & Fleck 1982; Ballesteros-Paredes et al. 1999a, 2008; Vásquez-Semadeni et al. 2008). So, it is difficult to imagine a turbulent velocity field inside the clumps that is completely random in such a way as to only provide support against gravity – the compressive component may rather foster core contraction. In addition, numerical simulations of cloud formation in the diffuse atomic ISM (e.g. Vásquez-Semadeni et al. 1995, 1996; Passot et al. 1995; Ballesteros-Paredes et al. 1999a, b; Audit & Hennebelle 2005; Heitsch et al. 2005, 2006; Vásquez-Semadeni et al. 2006, 2007; Hennebelle & Audit 2007) and of star formation in turbulent, self-gravitating clouds (e.g. Klessen, Heitsch & Mac Low 2000; Heitsch, Mac Low & Klessen 2001; Bate, Bonnell, & Bromm 2003; Vásquez-Semadeni et al. 2005, 2007) show that the velocity fields are organized at all scales, exhibiting a continuity from the large scales outside the clumps all the way to their interiors.

The large-scale compressions can be of turbulent origin (e.g., passing spiral arm shocks, supernova shells, or simply the general transonic turbulence in the diffuse medium) or of gravitational origin (e.g., large-scale gravitational or magneto-gravitational instabilities; Elmegreen 1991; Kim, Ostriker & Stone 2002; Field, Blackman, & Keto 2008). The self-gravitating simulations mentioned above exhibit gravitationally driven motions up to the largest scales. In particular, Vásquez-Semadeni et al. (2007, hereafter Paper I) have presented simulations of molecular cloud formation by generic compressions in the diffuse atomic ISM and of its subsequent collapse and star-forming stage, using the SPH/N-body code GADGET (Springel et al. 2001), complemented with parameterized heating and cooling taken from Koyama & Inutsuka (2002) and a sink-particle prescription (Jappsen et al. 2005). In these simulations, the clouds that formed acquired their initial turbulence from instabilities of the compressed layer (Vishniac 1994; Walder & Folini 1998; Koyama & Inutsuka 2002; Heitsch et al. 2005, 2006; Vásquez-Semadeni et al. 2006), but soon they became gravitationally unstable and began contracting. This contraction phase was nevertheless characterized by a virial-like energy balance with \( |E_{\text{grav}}| \sim 2E_{\text{kin}} \), which was however due to the gravitational contraction, not to virial equilibrium. During the global contraction, clumps produced by the initial turbulence proceeded to collapse on their own, forming what resembled low-mass star forming regions.

In Paper I, we speculated that the global contraction might be halted by stellar energy feedback before the global collapse was completed. However, here we forgo that speculation, and take the simulation at face value, presenting a preliminary study of the physical conditions in the region where the global collapse finally converges, showing that they resemble the physical conditions of high-mass star forming regions, thus suggesting that such regions may be in generalized gravitational collapse rather than in a state of turbulent “support”.

2. The numerical model

The simulation we consider is the one labeled L256Δv0.17 in Paper I. We refer the reader to that paper for details. Here we just mention that it is an SPH simulation with self-gravity, parameterized heating and cooling implying a thermally bistable medium, using \( 3.24 \times 10^6 \) particles, using sink particles, and initially set up to produce a collision of streams of diffuse gas (at the same density as
Figure 1. Column density plot of the central 50 pc of this simulation in the $y$-$z$ plane at $t = 23.4$ Myr, integrating over the central 8 pc along the $x$ direction. The box shows the region analyzed in [3]. The dots show the stellar objects (sink particles) already formed in the simulation by this time. Radial filamentary streams of intermediate-density gas are seen to still be accreting onto the central cloud.

By $t = 23.4$ Myr, the global collapse is completed, although the residual turbulence causes the motions to have a random component, so that the collapse center spans several parsecs across. Figure 1 shows a column density of the central 50 pc of this simulation in the $y$-$z$ plane at $t = 23.4$ Myr, integrating over the central 8 pc along the $x$ direction. The dense cloud is seen near the center of the image, with streams of gas still infalling onto it. A region 8 pc on a side containing the cloud is indicated by the square, for which animations can be found at [http://www.astrosmo.unam.mx/~e.vazquez/turbulence/movies.html](http://www.astrosmo.unam.mx/~e.vazquez/turbulence/movies.html) These
animations show the evolution of the central 8 pc of the simulation for $22.1 \leq t \leq 24.7$ Myr, showing a violent collapsing evolution in which infalling clumps of gas interact but do not entirely merge, but rather undergo shredding and distortion. It is this violent region that we analyze in the next section.

3. Physical conditions of clumps and cores in the collapse center

Figures 2a and 2b show two views of two parsec-sized clumps within the 8-pc cloud, to we refer as “Clump A” and “Clump B”. Note that these are just cubic boxes enclosing the dense clumps, rather than actual clumps defined by any clump-finding algorithm. Their properties can be compared with the observed typical properties of clumps in high-mass star forming regions. We do this by interpolating the SPH data for the central 8-pc region into a fixed grid with a resolution of $256^3$. Clump A, which has a size of 1.5 pc per side, has a mass $\mathcal{M} = 1400 M_\odot$, a mean density of $\langle n \rangle = 1.27 \times 10^4$ cm$^{-3}$, and a three-dimensional velocity dispersion $\sigma = 3.6$ km s$^{-1}$. Clump B, in turn, has a linear size of 0.8 pc, a mass $\mathcal{M} = 300 M_\odot$, a mean density of $\langle n \rangle = 1.72 \times 10^4$ cm$^{-3}$, and a velocity dispersion $\sigma = 2.8$ km s$^{-1}$. So, in general these properties compare well with those quoted in §1., except perhaps for slightly lower mean densities than typical, which can be understood as a consequence of our usage of cubic boxes rather than clumps. The boxes include some lower-density gas. On the other hand, our densities fare in well with those reported for massive starless clumps in the Cygnus X molecular complex by Motte et al. (2007).

Within these clumps, we identify cores by applying a simple clump-finding algorithm based on finding connected sets of grid points whose densities are above a certain threshold. For this preliminary analysis, we consider a single threshold $n_{\text{thr}} = 5 \times 10^4$ cm$^{-3}$, leaving us with 20 cores, 14 of which have $M > 4M_\odot$. For each core, we measure its mass, mean density, and velocity dispersion, and estimate its size as $R \approx (3V/4\pi)^{1/3}$, where $V$ is its volume. These properties can be compared with those reported by recent surveys of cores in high-mass star forming regions, such as that by Motte et al. (2007).
Figure 3. Histograms of the size (top left), mass (top right), mean density (bottom left) and three-dimensional velocity dispersion (bottom right) of the cores within Clumps A and B of the simulation (solid lines), normalized to the peak of the histogram. Dotted lines: same for the core sample in Cygnus X reported by Motte et al. (2007), except for the velocity dispersion, since their observations were performed in the 1.2 mm continuum. The peaks of the distributions are seen to coincide for size, mass and mean density. The reasons for the simulation distributions being narrower are discussed in the text.

for the Cygnus X region. These authors give these data for a sample of 129 dense cores with sizes $\sim 0.1$ pc, masses $4$–$950 M_\odot$, and mean densities $\sim 10^5$ cm$^{-3}$. In order to compare their data to the cores in our clumps, we fortuitously select the first 57 cores (those in the first page) in their Table 1 and show the distribution of their properties in the histograms presented in Fig.3 by the dotted lines. Superimposed on these histograms, the solid lines show the corresponding distributions for the 14 cores more massive than $4 M_\odot$ in Clumps A and B of our simulation. We see that, although the distributions of the Cygnus X cores are in general broader than those of the cores in our simulation, the peaks of the distributions match for size, mass, and mean density.

The fact that the distribution of densities for the cores in the simulation is narrower than the Cygnus X one is most likely a result of our sample being significantly smaller than that for Cygnus X, and of our having considered only a single density threshold for defining the cores. Our previous experience with this clump-finding method is that the mean density of the cores found is generally within less than one order of magnitude of the threshold density. This limitation is also the probable cause of the absence of the small-size tail of the cores in the
simulation, since smaller cores should appear when higher density thresholds are considered. So, in order to obtain a wider range of densities, masses and sizes, it is necessary to consider a suite of density thresholds. We plan to do it in the final study, to be presented elsewhere.

4. Conclusions

In this contribution we have presented preliminary numerical evidence that the physical conditions in high-mass star forming regions can arise from global gravitational infall, with the velocity dispersions being caused primarily by infall motions rather than random turbulence. The evidence comes from the first study of core properties in a simulation of the entire evolution of a molecular cloud, from its formation in the diffuse atomic ISM to its gravitational collapse. Although the analysis presented here is only preliminary, it is consistent with recent suggestions, based on comparisons between simulations and observations, that molecular clouds (e.g., Hartmann & Burkert 2007) and clumps (e.g. Peretto, Hennebelle & André 2007) may be in a state of gravitational collapse. If confirmed, these suggestions point towards a return to the original suggestion by Goldreich & Kwan (1974) that the observed linewidths in molecular clouds are due primarily to gravitational contraction. This suggestion was dismissed by Zuckerman & Palmer (1974) through the argument that this would imply a much larger average star formation rate in the Galaxy than observed. However, it is possible that this criticism may be overcome if magnetic field fluctuations in the clouds imply that some parts of them are magnetically supported so that only the non-supported parts of the clouds undergo collapse (Hartmann, Ballesteros-Paredes, & Bergin 2001; Elmegreen 2007), and the star formation rate is then regulated by stellar feedback, with globally collapsing motions arising only for those regions that manage to “percolate” through the field fluctuations and the stellar-feedback motions. We plan to perform simulations including magnetic support and stellar feedback in future studies to investigate this possibility.

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