The effects of a compressive velocity pulse on a collapsing turbulent clump

G. Arreaga-García

Departamento de Investigación en Física de la Universidad de Sonora, México. Apdo. Postal 14740, Hermosillo, 83000 Sonora, México.

Received XXXX, accepted XXXX
Published online XXXX

Key words – stars: formation; – physical processes: gravitational collapse, hydrodynamics; – methods: numerical;

High-resolution hydrodynamical simulations are presented to follow the gravitational collapse of a uniform turbulent clump, upon which a purely radial compressive velocity pulse is activated in the midst of the evolution of the clump, when its turbulent state has been fully developed. The shape of the velocity pulse is determined basically by two free parameters: the velocity \( V_0 \) and the initial radial position \( r_0 \). In the present paper, models are considered in which the velocity \( V_0 \) takes the values 2, 5, 10, 20, and 50 times the speed of sound of the clump \( c_0 \), while \( r_0 \) is fixed for all the models. The collapse of the model with \( 2c_0 \) goes faster as a consequence of the velocity pulse, while the cluster formed in the central region of the isolated clump mainly stays the same. In the models with greater velocity \( V_0 \), the evolution of the isolated clump is significantly changed, so that a dense shell of gas forms around \( r_0 \) and moves radially inward. The radial profile of the density and velocity as well as the mass contained in the dense shell of gas are calculated, and it is found that (i) the higher the velocity \( V_0 \), the less mass is contained in the shell; (ii) there is a critical velocity of the pulse, around \( 10c_0 \), such that for shock models with a lower velocity, there will be a well defined dense central region in the shocked clump surrounded by the shell.

1 Introduction

The propagation of shock waves arises in many astrophysical systems. In particular, there is ample observational evidence on the interaction of a shock with a gas structure, see for instance [Hwang et al. (2005)] who reported Chandra images of a shocked cloud being torn apart by shear instabilities in the Puppis A supernova remnant.

Further observational evidence of the shock–gas interaction has been provided by [Nutter et al. (2006)] who presented submillimetre measurements to explain the difference in the star formation activity of the clumps L1688 and L1689 of the \( \rho \) Ophiuchi molecular cloud complex. Indeed, these authors proposed that both clumps are being affected by members of the Upper Scorpius OB association, so that there is triggered star formation at different rates because the distance from the clumps to the most massive and luminous nearby component of the Upper Scorpius OB association is different.

* Corresponding author: e-mail: guillermo.arreaga@unison.mx
In addition, interferometric observations have revealed that the cores L1689B and L694-2 seem to collapse faster than their spontaneous collapse would indicate, as their infall velocities were observed to be faster than expected, see Lee et al. (2007). Thus, it was theoretically suggested by Seo et al. (2013) that these cores may be strongly influenced by an external factor, for example, turbulence, or an external pressure.

With regard to the theoretical aspect, papers on computational simulations of the interaction of a shock and gas clouds started to appear many decades ago, see for instance Stone & Norman (1992). These authors considered a 10 Mach shock that impacted on a cloud, so that its three-dimensional evolution led to its total disruption. More recently, other authors have also found that gas clouds are destroyed by an incident shock wave, among others, see Nakamura et al. (2006), Pittard et al. (2009), Pittard et al. (2010), Pittard et al. (2016).

The previous studies of Stone & Norman (1992), Nakamura et al. (2006), Pittard et al. (2009), Pittard et al. (2010), Pittard et al. (2016) are concerned with the destruction of interstellar clouds by shock waves. A more interesting scenario for star formation is based on the idea that a bound gas structure can be compressed by a shock to the point that its collapse can be triggered. In fact, Boss (1995) investigated this possibility, so that a radially inward velocity perturbation induced the collapse of a rotating centrally condensed three-dimensional core. In addition, Vanhala & Cameron (1998) demonstrated that the interaction of a planar shock wave with a centrally concentrated three-dimensional cloud is capable of triggering the gravitational collapse of the cloud, when radiative cooling in their smoothed particle hydrodynamics (SPH) simulations was taken into account.

Subsequently, using simulations limited to one radial dimension, Gomez et al. (2007) investigated whether a velocity pulse can trigger the formation of prestellar core when it strikes a gas cloud. These authors proposed a mathematical function such that the shape of the velocity pulse is mainly determined by the following parameters: the velocity $V_0$, the radii $r_0$ and $r_1$, and the increments on these radii $\delta r_0$ and $\delta r_1$, all of which are described in Section 2.2 of the present paper. These authors acknowledge that their setup was somewhat unphysical since it restricts the nature of the compressive wave to "one-dimensional" spherical shells.

In this paper, three-dimensional high-resolution hydrodynamical simulations of the interaction of the velocity pulse proposed by Gomez et al. (2007) with a turbulent clump are presented. Models are considered in which the velocity $V_0$ takes the values 2, 5, 10, 20 and 50 times the speed of sound of the clump, while the other parameters are fixed.

It should be emphasized that consequently with the previous hypothesis, the initial energies of the isolated turbulent clump of this paper are chosen to make it to collapse spontaneously, even without the compressive velocity pulse. The papers quoted previously of other authors like Stone & Norman (1992), Nakamura et al. (2006), Pittard et al. (2009), Pittard et al. (2010).
Pittard et al. (2016) investigated the effect of shock waves on clumps and clouds that would otherwise not collapse.

It should be emphasized that Hennebelle et al. (2003) investigated numerically the effects of a steady increase in the external pressure on the collapse of a prestellar core. For slow to moderate compression rates, subsonic infall velocities were observed to develop in the outer parts of the core. These authors also found that “a compression wave is driven into the core, thereby triggering collapse from the outside in”. This observation, together with the model of Gomez et al. (2007) have been the physical motivation of this paper, so that we have an incident three-dimensional spherical velocity pulse to simulate the effect of a larger, already collapsing cloud on an embedded turbulent clump.

In this paper, the kinetic energy of the clump is provided by means of a velocity field assigned according to a decaying, curl-free turbulent spectrum. At the end of the simulation run, a lot of fragmentation is seen to occur in the central region of the clump, as was previously observed in other simulations, see for instance Offner et al. (2009) and Offner et al. (2010). Later, when the first stage of evolution of the clump has passed and the turbulence has reached a fully developed state, a radially inward velocity pulse is activated, so that its effects on the subsequent evolution of the clump can be studied.

Consequently, the present paper is similar to that of Offner et al. (2009) and Offner et al. (2010) with the addition of a spherical compressive velocity pulse, executed with the fully-parallelized publicly available code Gadget2, which is based on the Smoothed Particle Hydrodynamics (SPH) technique, see Springel (2005) and Springel et al. (2001).

In addition, when gravity has produced a substantial contraction of the clump, the gas begins to heat, so that its increase of temperature is taken into account by means of a barotropic equation of state proposed by Boss et al. (2000). It should be mentioned that the equation of state is a very important factor on triggered star formation in molecular clouds, as the post-shock densities depend on the square of the Mach number of the shock wave, and therefore higher compression factors can be reached in isothermal simulations than in the adiabatic case. Foster & Boss (1996) and Foster & Boss (1997) concluded that for high-velocity shocks (greater than 100 km/s) the post-shock material is heated and becomes adiabatic. In these cases, the cloud can be destroyed. For low-velocity shocks, the post-shock material remains isothermal and high compression factors can also be achieved: self-gravity then leads to collapse. It was soon realized that the velocity of the shock together with the equation of state can make the difference between the two scenarios mentioned above, that is, triggered collapse or destruction of the gas structure.

The outline of the paper is as follows. In Section 2 the physical state of the clump, including its turbulent velocity spectrum, its initial energy conditions; the implementation of the velocity pulse and some computational details of the evolution are described. In Section 3 the main results of the simulations are presented by means of iso-density and velocity
plots. In Sections 4 and 5, a physical characterization of the simulation output is reported by means of plots of the density and velocity radial profile. In Section 6, a comparison between models with an equal distance from the shell of dense gas to the clump centre is presented. Finally, in Section 7 and 8, the main results and conclusions are summarized.

2 The physical system and the computational method

2.1 The clump

The gas structure considered in this paper has a radius of $R_0 = 2.0 \times 10^{18}$ cm $\equiv 0.65$ pc and a mass of $M_0 = 185 M_\odot$. Thus, the average density and the corresponding free fall time of this gas structure are $\rho_0 = 1.08 \times 10^{-20}$ g cm$^{-3}$ and $t_{ff} \approx 2.01 \times 10^{13}$ s $\equiv 0.63$ Myr, respectively. The values of $R_0$ and $M_0$ are very similar to those used by Offner et al. (2009) and Offner et al. (2010).

According to the naming convention introduced by Bergin et al. (2007), which is based on the mass and size of the gas structures, the one considered in the present paper is usually referred to as a gas clump. The physical state of the clump and the initial conditions implemented are next explained, in Sections 2.2–2.5.

2.2 The velocity pulse

The mathematical function for describing the velocity pulse has been taken from Eq. 2 of Gomez et al. (2007), which is given by

$$v(r) \approx \begin{cases} 
0 & \text{for } r < r_0 - \delta r_0 \\
V_0 \sin \left[ \frac{\pi}{2} \left( \frac{r - r_0}{\delta r_0} \right) \right] & \text{for } r_0 - \delta r_0 < r < r_0 + \delta r_0 \\
V_0 \sin \left[ \frac{\pi}{2} \left( \frac{r - r_1}{\delta r_1} \right) \right] & \text{for } r > r_0 + \delta r_0
\end{cases} 
$$

(1)

where $V_0$ determines the amplitude of the wave, for which it is the most important parameter, so that it will be varied later to define the models, see Table II of Section 3. Other parameters are $r_0$, $r_1$ which determine the initial radii where the pulse will be activated, and they are fixed as $r_0 = 0.8$, and $r_1 = \frac{1 + (r_0 + \delta r_0)}{2} = 0.95$, where the width of the wave is controlled by the parameters $\delta r_0 = 0.1$ and $\delta r_1 = \frac{1 - (r_0 + \delta r_0)}{2} = 0.05$. It should be emphasized that the radii $r_0$, $r_1$, $\delta r_0$ and $\delta r_1$ are all given in terms of the initial radius of the clump, $R_0$.

The function $v(r)$ can be taken entirely as the radially inward component of the velocity field, so that this paper can be considered as (i) another implementation of the idea previously considered by Boss (1995) (using another mathematical function) and (ii) a generalization to three-dimensions of the one-dimensional simulations calculated by Gomez et al. (2007).

\footnote{There is presumably a mistake (typo) in Eq. 2 of Gomez et al. (2007) so that in this paper we changed the sign.}
Let the coordinates of a particle be given by \((r, \theta, \phi)\), where \(r\) is the radial distance, \(\theta\) is the polar angle and \(\phi\) is the azimuthal angle. Then, the relation between the velocity components in spherical and Cartesian coordinates is

\[
\begin{align*}
    v_r &= \sin(\theta) \cos(\phi) v_x + \sin(\theta) \sin(\phi) v_y + \cos(\theta) v_z \\
    v_\theta &= \cos(\theta) \cos(\phi) v_x + \cos(\theta) \sin(\phi) v_y - \sin(\theta) v_z \\
    v_\phi &= -\sin(\phi) v_x + \cos(\phi) v_y.
\end{align*}
\]

so that it can be assumed that the left hand side of Eq. 2 is given by \(v_r = v(r)\), as shown in Eq. 1, while the polar and azimuthal components are \(v_\theta \approx 0\) and \(v_\phi \approx 0\), respectively.

Thus, the Gauss–Jordan elimination method described in Press et al. (1992) can be used to solve these equations simultaneously for each simulation particle in order to get the Cartesian components \(v_x, v_y,\) and \(v_z\), which are needed for the evolution code, see Section 2.5.

The velocities of the gas particles actually given to the Gadget2 code at the initial time are shown in Fig. 1.

Let us consider now Fig. 1. The curves with label \(C_{t=0}\) describe the radial velocity profile of the clump at the initial evolution time, so that the homogeneous distribution of matter is evident. At the time \(t/t_{ff} = 0.299\), the matter distribution of the clump has obviously changed as the curves with label \(C_{t=0.299}\) indicate. It should be noted that the outermost particles of the clump expand outwards spontaneously, as can be seen in the right panel of Fig. 1. This happens because the turbulent clump is not in hydrodynamic equilibrium and there is no external pressure acting upon it. However, this expansion does not take place only radially, as the outermost particles may have a non-zero tangential component of the velocity in addition to the radial component already seen in this panel.

However, only those particles within \(r_0 - \delta r_0 < r < r_0 + \delta r_0\) (an interval of \(\approx 0.8 < r < 0.95\)) are part of the velocity pulse, so that they have been assigned a radially inward velocity. Because of this, a discontinuity in the tangent component of the velocity has been imposed, as can be seen in the small fall in the magnitude of the velocity (shown in the left panel of Fig. 1) exactly at the radius \((\approx 0.95)\) where the radial component of the velocity (shown in the right panel of Fig. 1) changes their sign from negative to positive values.

### 2.3 The turbulent velocity

In order to generate the turbulent velocity spectrum, a mesh with a side length equal to the clump radius \(R_0\) is used, so that the size of each grid element of this mesh is \(\delta = R_0/N_g\) and the mesh partition is determined by \(N_g = 128\). In Fourier space, the partition is given by \(\delta K = 1/R_0\), so that each wavenumber \(K\) has the components \(K_x = i_x \delta K, K_y = i_y \delta K\) and \(K_z = i_z \delta K\) where the indices \(i_x, i_y, i_z\) take integer values in the range \([-N_g/2, N_g/2]\) to cover all the mesh.

---

2 For details about the radial partition of these plots, see Section 4.
The initial power of the velocity field must be given by

$$P(K) = \left\langle |v(K)|^2 \right\rangle \approx |K|^{-n}$$  \hspace{1cm} (3)

where the spectral index \( n \) is a constant, \( n = -1 \). Thus, following [Dobbs et al. (2005)] and [Arreaga (2017)] and [Arreaga (2018)] the components of the particle velocity, in the case of a diverge-free turbulent spectrum, are given by

$$v_{CF}(r) \approx \sum_{i} x_{i}, y_{i}, z_{i} |K|^{\frac{-n}{2}} K \sin (K \cdot r + \Phi_K)$$  \hspace{1cm} (4)

where \( \Phi_{Kx}, \Phi_{Ky}, \) and \( \Phi_{Kz} \) are random phases of the wave and \( r \) is the particle position in real space.

### 2.4 Initial energies

In the standard SPH formulation, the thermal, kinetic and gravitational energies of the set of gas particles are calculated by

$$E_{\text{ther}} = \frac{3}{2} \sum_{i} m_{i} \frac{P_{i}}{p_{i}}$$
$$E_{\text{kin}} = \frac{1}{2} \sum_{i} m_{i} v_{i}^2,$$
$$E_{\text{grav}} = \frac{1}{2} \sum_{i} m_{i} \Phi_{i}$$  \hspace{1cm} (5)

where \( P_{i} \) is the pressure and \( \Phi_{i} \) is the gravitational potential at the location of particle \( i \), with velocity \( v_{i} \) and mass \( m_{i} \), to be defined in Section 2.5. It should be kept in mind that all the SPH particles of a simulation must be used in the summation of Eq. 5.

Now, let \( \alpha \) be defined as the ratio of the thermal energy to the gravitational energy and let \( \beta \) be the ratio of the kinetic energy to the gravitational energy, so that

$$\alpha \equiv \frac{E_{\text{ther}}}{|E_{\text{grav}}|}$$  \hspace{1cm} (6)
and

$$\beta \equiv \frac{E_{\text{kin}}}{|E_{\text{grav}}|}$$  \hspace{1cm} (7)

In this paper, the value of the speed of sound \( c_{0} \) is fixed at 34247.56 cm/s, so that

$$\alpha \equiv 0.24$$  \hspace{1cm} (8)

for all the shock models and for the isolated clump model as well.

Another very useful quantity to characterize the physical state of a gas structure is the so-called virial parameter, which is defined observationally by

$$\beta_{\text{vir}} \equiv \frac{5 \sigma_{1D}^2 R}{G M}$$  \hspace{1cm} (9)

where \( G \) is Newton’s gravitational constant, \( M \) and \( R \) are the mass and radius of a general gas structure, and \( \sigma_{1D} \) is the intrinsic one-dimensional velocity dispersion of the hydrogen.
molecule of mean mass. Assuming isotropic motions, a three-dimensional velocity dispersion can be simply estimated by $\sigma_{3D} = \sqrt{3} \sigma_{1D}$. It should be noted that a gas structure in virial equilibrium would have

$$\beta_{\text{vir}} = 1$$

(10)

so that, using the mass and radius of the clump described in Section 2.1 in Eq.9 together with Eq.10 a value of $\sigma_{1D} = 1.44$ km/s is obtained.

The magnitude of the velocity field described in Eq.4 of Section 2.3 has been calibrated so that the three-dimensional velocity dispersion of the simulation particles, $\sigma_{3D}^{s}$, has been calculated to be equal to $\sigma_{1D}$, so that $\sigma_{3D}^{s} = 1.44$ km/s. In this case, the approximate virial parameter of the turbulent clump described in Section 2.1 and 2.3 would initially take a value a little bit below 1.

In any case, when the velocity pulse is activated in the turbulent clump, there will be a value of $\beta_{\text{vir}}$ and $\beta$ for each model. Only $\beta$ is presented in Table I with the purpose of characterizing further the dynamical state of the corresponding clump and shock models as well.

Xing et al. (2018) reported the values of the virial parameter observed in many gas cloud cores, which in general were found to be smaller than or around the value 1. In addition, Bertoldi & McKee (1992) found that the observed virial parameter depends on the total mass of the gas structure. Kauffmann et al. (2013) discussed how the value of the virial parameter determines the later evolution of a self-gravitating, non-magnetized gas structure: a virial parameter above 2 indicates that the gas structure is unbound and may expand, while one below 2 suggests that the gas structure is bound and may collapse.

Theorists have often used another expression for the virial parameter, for instance, $\beta_{\text{vir}} = 2 a \beta$, where $\beta$ is the dimensionless ratio defined in Eq.7 and $a$ is a numerical factor which is empirically included to take into account modifications of non-homogeneous and non-spherical density distributions.

It must be recalled that the important issue for the present paper is to have initially a globally collapsing clump, as was mentioned in Section II. In addition, it must be mentioned that Peretto et al. (2006) observed the clump NGC 2264-C and found it to be in a global state of collapse, far from hydrostatic equilibrium, as its virial parameter is around 0.2, which indicates that the clump is very unstable gravitationally.

2.5 Evolution code, resolution and equation of state

The temporal evolution of all the models of the present paper has been solved using the particle-based computer program Gadget2, see Springel (2005) and also Springel et al. (2001). Gadget2 is based on the tree-PM method for computing the gravitational forces and on the
standard SPH method for solving the Euler equations of hydrodynamics. Gadget2 implements a Monaghan–Balsara form for the artificial viscosity; see Monaghan & Gingold (1983) and Balsara (1995). The strength of the viscosity is regulated by the parameter $\alpha_\nu = 0.75$ and $\beta_\nu = \frac{1}{2} \times \alpha_\nu$; where $\alpha_\nu$ and $\beta_\nu$ are coefficients of linear and quadratic viscosity; see Eqs 11 and 14 in Springel (2005). In the simulations presented in this paper, the Courant factor is fixed at 0.1.

Following Truelove et al. (1997) and Bate & Burkert (1997), the smallest mass of a particle that the SPH calculation must resolve in order to be reliable is given by $m_p / m_r < 1$, where $m_p$ is the mass of the simulation particle and $m_r \approx M_J / (2N_{\text{neigh}})$, so that $N_{\text{neigh}}$ is the number of neighbouring particles included in the SPH kernel and $M_J$ is the Jeans mass, which can be expressed by

$$M_J = \frac{4}{3} \pi \rho \left( \frac{\lambda_J}{2} \right)^3 = \frac{\pi^{\frac{5}{2}}}{6} \frac{c^3}{\sqrt{G^2 \rho}} \quad (11)$$

where $\lambda_J$ is the Jeans wavelength, $c$ is the instantaneous speed of sound, $\rho$ is the local density, and $G$ is Newton’s gravitation constant. In addition, the values of the density and speed of sound must be updated according to the following equation of state:

$$p = \frac{c^2}{\gamma - 1} \left[ 1 + \left( \frac{\rho}{\rho_{\text{crit}}} \right)^{\gamma - 1} \right], \quad (12)$$

which was proposed by Boss et al. (2000) where $\gamma = 5/3$ and for the critical density the value $\rho_{\text{crit}} = 5.0 \times 10^{-14} \text{ g cm}^{-3}$ is assumed.

Let us say something about this equation of state. The ideal equation of state is a good approximation to the thermodynamics of the observed star forming regions, which basically consist of molecular hydrogen cores at 10 K with an average density of $1 \times 10^{-20} \text{ g cm}^{-3}$. Furthermore, once gravity has produced a substantial core contraction, the gas begins to heat. Therefore, the most important free parameter is then the critical density $\rho_{\text{crit}}$, which determines the change of thermodynamic regime from isothermal to adiabatic. It should be emphasized that this approach is introduced with the purpose of avoiding the consideration of a radiative transfer problem coupled with an energy equation in the hydrodynamics equations. Indeed, Whitehouse & Bate (2006) studied the collapse of cores including radiative transfer in the flux-limited diffusion approximation. These authors observed important differences in the dependence of temperature on density. However, Arreaga et al. (2008) compared the results of simulations of the collapse of the uniform density core with those of Whitehouse & Bate (2006) at several values of $\rho_{\text{crit}}$ and found that the barotropic equation of state behaves quite well within the range of $\rho_{\text{crit}}$ between $10^{-14} - 10^{-11} \text{ g cm}^{-3}$. Based on these results, in this paper the parameter $\rho_{\text{crit}}$ has been fixed at the value mentioned above.

Assume that a typical peak density of $\rho = 1.0 \times 10^{-11} \text{ g cm}^{-3}$ can be reached in the late evolution of the shock models and for the turbulent clump considered in the present
paper as well, so that the total number of particles in a simulation is \( N_p = 15,417,343 \). Thus, the particle mass is given by \( m_p = 1.19 \times 10^{-5} M_\odot \) and the Jeans mass is \( M_j \approx 0.001 M_\odot \), so that the minimum mass is \( m_r \approx 1.34 \times 10^{-5} M_\odot \), since \( N_{\text{neigh}} = 40 \). Therefore, the ratio of masses is given by \( m_p/m_r = 0.89 \) and then the desired resolution is achieved in our simulations.

Thus, for the stated average density \( \rho_0 \) of the clump, in this calculation it will be initially isothermal and only when the peak density has increased by six orders of magnitude, it will become adiabatic.

### 3 Results

#### 3.1 Visualization

The main outcome of each model is illustrated by means of an iso-density plot, in which a slice of the simulation particles is used from the last snapshot available. The width of the slice is determined so that it contains around 10,000 gas particles; the characteristic width of the slice in terms of the clump radius \( R_0 \) is of the order of \( 3 \times 10^{-4} \). In addition, the slice is parallel to the \( x - y \) plane and its height along the \( z \)-axis is determined by the \( z \)-coordinate of the highest density particle. A bar located at the bottom of each iso-density plot shows the range of values for the base 10 logarithm of the ratio of the peak iso density to the average density of the initial clump, that is, \( \log_{10}(\rho_{\text{max}}(t)/\rho_0) \). It must be emphasized that this logarithm scale of density is used to (i) set a gray scale, so that the different density regions can be distinguished in the iso-density plots to show in Sections 3.2 and 3.3.5; (ii) set a variation scale of density, so that a density width can be defined in order to determine the mass contained in a shell of dense gas, see Section 5; (iii) follow the position of the shell of dense gas with respect to the clump centre for all the evolution time, see Section 6.

It should be explained that the vertical and horizontal axes of all the iso-density plots indicate the length in terms of the radius \( R_0 \) of the clump. Hence, the Cartesian \( x \)- and \( y \)-axes vary initially from -1 to 1. However, in order to facilitate the visualization of the last configuration obtained, the same length scale per side is not used in all the plots. In addition, for each iso-density plot, a velocity plot is also presented, which is constructed using the same slice of simulation particles, so that an arrow is located at the site of each particle, with its length being proportional to the total magnitude of the velocity.

The global evolution of the models will be described in Sections 3.2 and 3.3. As desired, all the models collapse, so that the peak density reached at every point in time of the evolution (where a snapshot of each model is available) is determined and shown in Fig. 2. Later, in order to characterize further the shock models, the behaviour of the radial profile of the density and velocity of the particles will be calculated and described in Section 4.
3.2 The clump model

It is well known that a turbulent velocity spectrum, such as the one implemented here, induces a lot of collisions between the particles, so that the density of some particles will be increased, in many places of the clump simultaneously. The initial compressive velocity pulse will steepen immediately into an inward-moving shock wave. Since the equation of state is initially isothermal, the compression factor will depend on the Mach number squared and thus the higher velocity shock waves will produce the highest post-shock densities, as is predicted by the so-called Rankine-Hugoniot jump conditions, see Landau & Lifshitz (1959). Such behaviour is manifested in the oscillations of the density curves shown in Fig. 2, so that the first stage of the evolution of the turbulent clump can be defined in this way.

The second stage can be identified at times beyond $0.1 t_{ff}$, in which the clump becomes more homogeneous, so that the peak density curve stretches almost horizontally, up to a time of around $0.8 t_{ff}$; the third stage can be seen at times $t$ within $0.8 t_{ff} < t < 1.0 t_{ff}$, at which a true collapse of the clump takes place, in a collapse time a little bit smaller than $t_{ff}$.

The evolution of the isolated turbulent clump has been followed up to the point when a lot of fragmentation is produced in its central region, so that a cluster of small over-densities can be seen in Fig. 5. Similar results have been obtained by many authors, so that there are papers studying the statistical properties of the resulting fragments, see for instance Bate et al. (2003), Bate (2012).

3.3 The overall evolution of the shocked clump

It should be emphasized that the velocity pulse, described in Section 2.2, is going to be activated in the middle of the second stage described in Section 3.2 when the clump has evolved up to time $t/t_{ff} = 0.299$, when the peak density is $\log (\rho_{max}/\rho_0) = 0.23$. The pre-impact state of the clump is illustrated in Fig. 4.

All the models produce the formation of a ring of high density gas at the outermost region of the clump, whose physical properties, as width, mass and size depend obviously on the magnitude of the velocity $V_0$. As this dense gas collapses locally, then the ring will fragment, so that the relevant timescales are those of the fragments and not the global free-fall time of the clump. In spite of this, we will use $t_{ff}$ as the normalizing factor of the evolution time.

It was mentioned that Fig. 2 shows that all the models considered in this paper collapse at a time $t_{col}$ less than the free-fall time of the isolated clump, $t_{ff}$. Clearly, $t_{col}$ depends on the Mach number of the incident velocity, related to $V_0$ and shown in Table 1. It can be appreciated that the collapse time $t_{col}$ varies in general from 0.3 to $0.9 \times t_{ff}$.

Another feature to be appreciated in Fig. 2 is that the non-linear evolution of the clump is reached very quickly, as follows. When the velocity pulse is activated in the gas clump,
the Rankine–Hugoniot jump conditions, which analytically predict an increase of pre-shock density on the order of 4, is clearly surpassed, hereby the density oscillations in the curves of Fig. 2 are of order 10–100 times the average density of the clump.

Lastly, it should be mentioned that the models terminate their evolution because the huge increase in density makes the time step of the runs extremely small, to the point that the further evolution of the models can not be followed.

In the subsequent sections 3.3.1–3.3.5, the details of the resulting configuration of each shock model will be described separately. To complement this description, in Section 6 an inter-model comparison will be presented.

### 3.3.1 The model S2

When the velocity \( V_0 \) takes its smallest value, \( 2c_0 \), for Model S2, the shell of dense gas is very thin initially. By the time \( 0.75 t_{ff} \), the shock reaches the interior region of the clump and a lower density of particles remain at the outer layers of the clump, so that the shell can hardly be distinguished.

Meanwhile, a higher density of particles is formed into the innermost region of the clump, so that the collapse goes faster there, although the cluster structure is not destroyed, so that it looks similar to that observed in Model C (when no velocity pulse was ever activated); see Fig. 5.

The set-up of this model is similar to that implemented by Gomez et al. (2007) as they used only one value of the velocity pulse, given by \( 2c_0 \), and two values of the parameter \( r_0 \). In the present paper, only one value of the parameter \( r_0 \) has been used, which is the same as one of the parameters used by Gomez et al. (2007) so that it was the one that led to a collapsing cloud.

### 3.3.2 The model S5

In Model S5 with \( V_0 = 5c_0 \), a dense shell of particles can clearly be seen. It moves towards the centre of the clump and grows in mass while keeping its spherical symmetry. At the time \( 0.68 t_{ff} \), two outward asymmetric flows of gas occur simultaneously, one along the positive and the other along the negative direction of the \( y \)-axis, as shown in Fig. 6. By the end of the simulation, this high density shell of particles is clearly visible in the innermost central region of the clump, so that the gas inside this enclosed region has a lower density of particles.

### 3.3.3 The model S10

When the velocity pulse increases to \( V_0 = 10c_0 \), many small protuberances appear along the dense shell of particles, so that the shell expels gas by means of these protuberances. As
happened in previous model, in this case, at the time $0.47 \ t_{ff}$, much more gas accumulates simultaneously along the positive and negative directions of the $y$-axis, trying to leave outward. The dense shell of particles moves inward, so that it becomes very thick and encloses a very small region inside; see Fig. 7.

### 3.3.4 The model S20

The evolution of Model S20, which has $V_0 = 20 \ c_0$, is very similar to that of Model S10. In this case, the gas protuberances are larger, so that they even show some curvature. In spite of this, the dense shell of particles does not show any sign of fragmentation.

There is an outflow of dense gas through the negative direction of the $y$-axis, which is more noticeable than in the previous models. The simulation ends quickly, because the peak density is reached in the shell, without giving time for the shell to move inward appreciably, as was the case in Model S10; see Fig. 8.

### 3.3.5 The model S50

In Model S50, for which the velocity $V_0$ takes the largest value considered in the present paper, the dense shell of particles is very thin. The increase of density after the shock is high enough to favour the fragmentation of the shell in many places throughout the shell simultaneously. However, as more particles of the clump envelope are still falling into the shell, it keeps its spherical symmetry. The simulation ends because some of the fragments of the shell reach their peak density so quickly, that there was no time for the shock to move anymore; see Fig. 9.

### 4 The radial profile of the density and velocity distributions

In order to characterize further the distribution of particles, their dynamics and the dense shell of particles in all the shock models considered above, in this section a radial partition of the spherical model is performed as follows.

The maximum radius $r_{\text{max}}$ to which the spherical clump has expanded by the end of its evolution time, has been determined for each model. Then, a radial partition of the spherical clump in $n_{\text{bin}}$ bins is made from 0 to $r_{\text{max}}$, so that the increments in radius are given by $\delta r = r_{\text{max}}/n_{\text{bin}}$; thus, all the particles contained in a radial bin within the radii $r_i$ and $r_i + \delta r$ are taken into account to calculate their average particle density, which is shown at radius $r_p = r_i + \delta r/2$ in the left panel of Fig. 10. It should be noted that the density $\rho_p$ and radius $r_p$ are normalized with the initial density and radius of the isolated clump, $\rho_0$ and $R_0$, respectively.

Several interesting observations can be made from the left panel of Fig. 10. First, it clearly shows that the greater the Mach number of the incident shock (the $V_0$ of the model),
the further away from the clump centre is formed the shell of dense gas. Second, it also shows that the larger the initial velocity of the pulse \( V_0 \), the lower the central density. Third, all the curves of the shock models follow the radial density profile of the isolated clump. Fourth, as expected on the basis of the Rankine–Hugoniot jump conditions, the oscillations in the density curve are more pronounced in the case of models with a large pulse velocity.

Taking advantage of this radial partition, the average velocity of the particles is calculated per radial bin, so that the result for the first snapshot was already shown in Fig. 11 while the result for the last snapshot available in each model is now presented in Fig. 11. Consider now Fig. 11. In the case of the clump model, the outer particles of the central region continue to fall towards the centre of the clump. This is also observed to occur in the low velocity \( V_0 \) shock models, namely, Models S2, S5 and S10. However, for the higher velocity \( V_0 \) shock models, namely Models S20 and S50, the central region shows no particles moving at all, until the radius at which the first dense shell is reached.

A velocity field similar to the one described above for Models S20 and S50 was observed by Hennebelle et al. (2003) in the cases of strongly supersonic, finite compression, where the external pressure on the core increased until it was halted once it was doubled, see his model with \( \phi = 0.1 \).

5 The mass of the shell

To calculate the mass contained in the dense shell, denoted by \( M_p \), we apply again the radial partition of the spherical model described in Section 4 to the last snapshot available, so that the radial bin at which the highest density value takes place must be now firstly obtained. In this case, a variation of density is also needed to define the width of the shell; let it be defined as \( \delta \rho_p \) with a value of \( \log_{10} (\delta \rho_p) = 0.5 \) for all the models. Thus, all those particles with a density within the range \( (\rho_p - \delta \rho_p, \rho_p + \delta \rho_p) \) and located within the radii \( (r_p - 2\delta l, r_p + 2\delta l) \) are selected to obtain the mass of the shell. The parameter \( \delta l \) has been chosen visually from Figs 6–9 so that there is one value for each shock model as follows: 0.03 for model S2; 0.06 for models S5 and S10; 0.033 for model S20 and 0.016 for model S50. The result of this calculation can be seen in the right panel of Fig. 10 against the the initial velocity of the shock model.

It is interesting to note that the larger the initial velocity \( V_0 \) of the pulse, the lower the mass \( M_p \) contained in the shell. However, it is remarkable that the mass contained in the shell is in general very large, so that the ratio of this mass to that of the clump ranges within 0.32–0.1.

\(^3\) Unfortunately, the masses calculated in this way, are going to be obtained for quite different evolution times; in spite of this, their comparison is interesting as it allows us to characterize quantitatively the last configuration available.
6 Time evolution of the distance of the shell to the clump centre

It was mentioned in Section 3 that the models were advanced in time as much as possible, up to the time when the time-step becomes prohibitively small for the simulations to evolve any further, so that in Sections 3.3.1-3.3.5 the last snapshots were chosen to illustrate the simulations outcome.

In this Section, an attempt is made to make an inter-model comparison, by calculating the distance of the dense shell of gas to the clump centre for the shock models, as follows. In Sections 4 and 5, the peak density in a radial partition was determined in order to define the width of the dense shell of gas. In this section we consider again this peak density to locate the shell of dense gas with respect to the clump centre, for all the snapshots available of each shock model. The result of this procedure is shown in Fig.13.

When the shock front is activated, there is an immediate increase of density, so that the shell of dense gas is located initially very close to $r_0$, the initial radius in the mathematical function of the velocity pulse, see Eq.1. Then, the shell moves radially inward as can be seen in Fig.13. Unfortunately, the evolution time reached for model S50 is quite small; for model S20, the shell of dense gas was followed up to a radius around $0.43 \times R_0$ from the clump centre. For models S10 and S5, the closest approaching distance to the clump centre was around $0.15 \times R_0$. The most interesting behaviour was observed for model S2, since there is a bounce of the shell of dense gas.

The horizontal dashed line shown in Fig.13 indicates the radius with which the snapshots for this inter-model comparison are now determined, since all the snapshots must have their shell of dense particles at an equal distance to the clump centre, given by this radius, as can be seen in the iso-density plots shown in Fig.14.

7 Discussion

The pulse velocities considered in this paper, the $V_0$ shown in Table 1, both in terms of the speed of sound and in the MKS system of units, are comparable with those used in the following papers: (i) Vanhala & Cameron (1998) who considered the range 10 to 50 km/s; (ii) Boss (1995) who used the range 0 to 25 km/s; and (iii) Gomez et al. (2007) who considered only one velocity given by twice their speed of sound, which corresponds to 0.4 km/s.

It should be mentioned that the papers of Vanhala & Cameron (1998) and Boss (1995) are not directly comparable with the present paper, as they considered planar shock waves, not spherical velocity pulses. Vanhala & Cameron (1998) defined a critical shock velocity of 20 km/s, which is required to obtain a triggered collapse of their spherical, rotating core. For shock velocities above it, around 45 km/s, the shocks are disruptive whereas for shock velocities below it, around (or less than) 10 km/s, the core rebounds and is torn apart. Boss (1995)
found that a shock wave striking a rotating core at a velocity of 25 km/s resulted in the ‘outside-in’ collapse of the core. Both Vanhala & Cameron (1998) and Boss (1995) consider a rotating centrally condensed core, but it seemed that rotation did not make any significant difference in the outcomes of the simulations.

In the case of the present paper, it was mentioned in Section 3.2, that the pulse was activated when the first stage of evolution of the clump has passed, so that the peak density does not increase significantly due to the random collisions between particles; thus, it is expected that the turbulence has reached at this time a fully developed state. This objective was also mentioned by Vazquez-Semadeni et al. (2008), who made a pre-run in their simulations, so that gravity was turned on only after 3.2 turbulent crossing times of evolution of the turbulent cloud.

The gas particles with a radially inward initial velocity given directly by the velocity pulse, that is, those that are originally located around a radius $0.8 R_0$, see Fig. 1, reach those particles located at smaller radii, giving place to the formation of the shell of dense particles observed in the present paper; this is a manifestation of the so-called ‘collect and collapse model’, simulated by Dale et al. (2007) However, there is a significant difference between these two scenarios, with particles going inward or outward, as the boundary conditions imposed on the moving shock are different, that is, for the inward case, there must be a rebound of those particles that reach the centre of the clump (reflective boundary conditions); one of these effects can be seen in Models S5 and S10 of the present paper, in which the dense shell of particles is very deformed as it approaches the centre of the clump and even stops moving inward. In the outward case, the outflow continues without any boundary. It should be emphasized that on the contrary to the observation of Vazquez-Semadeni et al. (2008), the plot Fig. 11 does not suggest any evidence for the occurrence of a shock bouncing at the center of the shock models. However, in this paper a bounce was observed only for Model S2, see Section 6.

It was mentioned in Section 3.1 that the infall velocities for the cores L1689B and L694-2 were observed to be faster than expected, see Lee et al. (2007). A theoretical model proposed by Seo et al. (2013) in which the collapse of the cores was modeled by means of a uniform density or as Bonner–Ebert spheres, demonstrated that these cores may have infall velocities up to -1.0 or -1.5 times the velocity normalized with the speed of sound, which indicates an enhanced collapse. Meanwhile, for the cores L1544 and L63, in which the collapse appeared to be normal, the magnitude of the infall velocity was around -0.5 times the speed of sound. These authors suggested that the former cores may be strongly influenced by an external factor.

From the results obtained in the simulations considered in the present paper, such an external factor can not be a velocity pulse with the parameters chosen here. According to

---

4 The magnitudes of the infall velocities reported here have been taken from fig. 6 of Seo et al. (2013).
Fig. 2, it can be observed that the overall collapse of the clump model was enhanced by the velocity pulse. However, the infall velocities of the low velocity shock models were observed to be a little bit smaller than those observed for the isolated clump model, see Fig. 11.

In addition, the observations of the core L1544 by Tafalla et al. (1998) and Williams et al. (1999) suggested that “the inner parts of the core are relatively stationary, and an approximately uniform velocity field has been established in the outer layers.” For the higher velocity $V_0$ shock models of this paper, namely Models S20 and S50, it can be very clearly seen that the central region of the clump shows no particles moving at all, until the radius at which the first dense shell is reached. The particle velocities in the inner region are essentially zero because of the short simulation time. It was also observed in Section 4 that the clump separates into two halves, so that there is one half with particles falling inward while there is another half in the exterior region with particles flowing outward.

Another feature to be remarked here is relative to considering the velocity pulse as a core formation mechanism, as was originally proposed by Gomez et al. (2007), see Section 1. In fact, using one-dimensional radial simulations and only one initial velocity of the pulse given by 2 times the speed of sound, Gomez et al. (2007) observed that once the shock reaches and bounces off the centre of their cloud, a central core is formed which is surrounded by a gas envelope.

In the present paper, three-dimensional simulations of a set-up similar to that proposed by Gomez et al. (2007) have been carried out. It should be mentioned that a direct comparison of the results of this paper with with the work of Gomez et al. (2007) can not be made, since their initial models were not prepared to collapse spontaneously. On the contrary, the dense central region in the present paper is formed even in the model without a velocity pulse, since our clump was prepared to collapse spontaneously.

In addition, in this paper several initial velocities of the pulse have been taken into account. The radial distribution of the density of the shock models shown in the left panel of Fig. 10 can be compared with the first line of the plots shown in Gomez et al. (2007) in their fig. 3. Moreover, in Fig. 11, it can be seen that the low velocity models have radial velocity curves with a behaviour very similar to that described by Gomez et al. (2007) in the third line of panels of their Fig. 3.

Therefore, on the basis of this limited comparison, the finding of Gomez et al. (2007) is here confirmed, that a dense central region is formed as a result of the shock–gas interaction. However, one prediction of the present simulations is that there is a critical initial velocity of the pulse such that for shock velocities below the critical velocity, a central dense region will be formed, but otherwise, the central region is almost empty of moving gas. As we mentioned in Section 4, a core configuration with a velocity field similar to the one described here, was obtained by Hennebelle et al. (2003) in the case of a core subjected to a strong external pressure.
A second prediction of this paper is that the central region strongly resembles the configuration obtained from the collapse of the isolated gas structure, without the velocity pulse, which in this case was obtained only for the smallest shock velocity, that of twice the speed of sound.

A last point to be emphasized is about the possibility of having fragmentation in the shock models studied in this paper. It seems that all the models have a certain tendency for the shell to fragment, as many cloudlets of dense gas are being formed along the shell. It is interesting to mention that there is another way in which fragmentation may occur. As was observed in Models S5, S10 and S20, some local turbulence develops in the outflow of gas in the negative direction of the $y$-axis. In Model S20, this effect is more noticeable, as can be seen in Fig. 12, where a zoom-in of that region is shown.

8 Concluding Remarks

Three-dimensional, high-resolution, hydrodynamical simulations of a compressive velocity pulse impacting inward radially on a turbulent clump have been presented. The structure of the velocity pulse depends on several parameters, and the most important one, the magnitude of the initial velocity $V_0$, has been varied systematically within the range 0–50 times the speed of sound $c_0$. This set-up was chosen to (i) reconsider and improve the one-dimensional radial simulations of Gomez et al. (2007) to explore its feasibility as a mechanism of core formation; (ii) implement the idea of triggered collapse worked out by Boss (1995) and Vanhala & Cameron (1998) and more recently by Hennebelle et al. (2003).

All the shock models showed a separation into an external region $r > 0.95 R_0$ expanding outwards and an inner region falling inwards. This is a direct consequence of the form of the initial velocity pulse, which also has positive velocities for $r > 0.95 R_0$. The central regions are not affected by what is happening outside since the particles inside have no knowledge of the radially converging shock wave. Consequently, the central regions all proceed to collapse like the model without the velocity pulse for the duration of the simulation. Since each model runs for a different length of time, then the model with the highest Mach number (the shortest simulation time) had lower central densities since the collapse of the central regions has not gone on for so long.

Some of the main conclusions to be drawn from the shock models calculated here are the following:

1. The turbulent clump collapses spontaneously a little before its free-fall time $t_{ff}$, so that its central region shows a lot of fragmentation, as is well known.

2. The velocity pulse speeds up the collapse of the turbulent clump, so that its new collapse times are shortened, as follows 0.31, 0.49, 0.69, 0.81 and $0.89 \times t_{ff}$, for the models the models S50, S20, S10, S5 and S2, respectively.
3. The pre-impact state of the clump in its central region is very similar to the outcome of the simulation with the lowest velocity pulse, Model S2, for which $V_0 = 2c_0$. The other shock models, Models S5–S50, exhibit a noticeable effect in changing the pre-impact configuration, so that a shell of dense particles is formed at the outermost region of the clump.

4. As expected, the physical properties of the shell, such as its position, width, mass, and dynamics, depend on the magnitude of the initial velocity $V_0$.

5. The mass contained in the shell is found to be large in general, ranging from $20–60 M_\odot$, and the higher the velocity $V_0$, the less mass is contained in the shell.

6. The central density of the shock models decreases as the velocity $V_0$ increases.

7. There is a dense gas structure in the central region of the shocked clump, which can be identified as a core, in the sense of [Gomez et al. (2007)] as its radial profile of density and velocity seem to indicate for Model S2.

8. In agreement with the observation of [Vazquez-Semadeni et al. (2008)] in this paper there is evidence for the occurrence of a shock bouncing at the center only for model S2, even though it is likely that the other shock models will also produce a shock bouncing too, provided that the evolution time be long enough.

9. Additionally, there is a critical velocity of the pulse, such that for shock models with a lower pulse velocity (around 10 times the speed of sound) this dense central region will also form.

10. The shock models studied here show ample possibilities of fragmentation, which can occur (i) along the shell of dense gas in the large velocity models, such as Model S50; (ii) in the small region of the outflow of gas, more noticeable in the moderate velocity models, such as Model S20; (iii) in the innermost central region of the shocked clump, where a cluster of small gas over-densities is formed only for the smallest velocity pulse, such as Model S2; so that this region is clearly inherited by the turbulent clump considered.

Acknowledgements. The author thankfully acknowledge the computer resources, technical expertise and support provided by the Laboratorio Nacional de Supercómputo del Sureste de México through the grant number O-2016/047.

References

Arreaga-García, G., Saucedo-Morales, J.C., Carmona-Lemus, J. and Duarte-Perez, R. 2008, Revista Mexicana de Astronomía y Astrofísica, 44, pp. 259–284.

Arreaga-García, G., 2017, Revista Mexicana de Astronomía y Astrofísica, 53, pp. 361–384.

Arreaga-García, G., 2018, Astrophysics and Space Science, 363, pp. 157-169.

Bacmann, A. and Pagani,L., 2008, atnf prop, 1418.

Balsara, D., 1995, J. Comput. Phys., 121, 357.

Bate, M.R., Bonnell, I.A. and Bromm, V., 2003, MNRAS , 339, pp. 577–599.
Bate, M.R., 2012, MNRAS, 419, pp. 3115–3146.
Bate, M.R. and Burkert, A., 1997, MNRAS, 288, 1060.
Bergin, E. and Tafalla, M., 2007, Annu. Rev. Astro. Astrophys., 45, 339.
Bertoldi, F. and McKee, C., 1992, ApJ, 395, pp.140-157.
Boss, A.P., 1995, ApJ, 439, pp.224-236.
Boss, A.P., Fisher, R.T., Klein, R. and McKee, C.F., 2000, ApJ, 528, 325.
Dale, J.E., I. A. Bonnell, I.A. and Whitworth, A.P., 2007, MNRAS, 375, pp. 1291-1298.
Dobbs, C.L., Bonnell, I.A. and Clark, P.C., 2005, MNRAS, 360, pp. 2–8.
Foster, P. and Boss, A.P., 1996, ApJ, 468, p.784.
Foster, P. and Boss, A.P., 1997, ApJ, 489, Issue 1, pp. 346-357.
Gomez, G.C., Vazquez-Semanedi, E., Shadmehri, M. and Ballesteros-Paredes, J., 2007, ApJ, 669, pp. 1042–1049.
Gonzalez-Samaniego, A., Vazquez-Semadeni, E., Gonzalez, R.F. and Kim, J., 2014, MNRAS, 440, pp.2357-2374.
Hennebelle, P., Whitworth, A. P., Gladwin, P. P. and Andre, Ph., 2003, MNRAS, 340, Issue 3, pp. 870-882.
Hwang, U., Flanagan,K.A. and Petre, R., 2005, ApJ, 635, pp. 355–364.
Kauffmann, S., Pillai, T. and Goldsmith, P.F., 2013, ApJ, 779, 185.
Landau, L. D. and Lifshitz, E.M., Fluid Mechanics. Course of Theoretical Physics, Vol. 6.
Lee, S.H., Park, Y., Sohn, J., Lee, W.C. and Lee, H.M., 2007, ApJ, 660, 1326.
Monaghan, J.J. and Gingold, R.A., 1983, J. Comput. Phys., 52, 374.
Nakamura, F., Mckee, C.F., Klein, R.I. and Fisher, R., 2006, ApJ, 164, pp. 477-505.
Nutter, D., Ward-Thompson, D. and Andre, P., (2006), MNRAS, 368,pp.1833-1842.
Offner, S.R., Kratter, Klein, R.I. McKee, C.F. and Krumholz, M.R., 2009, ApJ, 703, pp.131-149.
Offner, S.R., Kratter, K.M., Matzner, C.D., Krumholz, M.R. and Klein, R.I., 2010, ApJ, 725, pp.1485-1494.
Peretto, N., Andre, P. and Belloche, A., (2006), à, 445, pp.979-998.
Pittard, J.M., Falle, S.A.E.G., Hartquist, T.W. and Dyson, J.E., 2009, MNRAS, 394, p. 1351-1378.
Pittard, J.M., Hartquist, T.W. and Falle, S.A.E.G., 2010, MNRAS, 405, p.821-838.
Pittard, J.M. and Parkin, E.R., 2016, MNRAS, 457, Issue 4, p.4470-4498.
Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., 1992, Numerical Recipes in Fortran
77, Second Edition, Cambridge University Press.
Springel, V., 2005, MNRAS, 364, 1105.
Springel, V., Yoshida, N. and White, S.D.M., 2001, New Astronomy, 6, 79.
Seo, Y. M., Hong, S.S. and Shirley, Y.L., 2013, ApJ, 769, pp.1-9.
Stone, J.M. and Norman, M.L., 1992, ApJ, 390, pp. L17.
Tafalla M., Mardones D., Myers P. C., Caselli P., Bachiller R. and Benson P. J., 1998, ApJ, 504, 900.
Truelove, J.K., Klein, R.I., McKee, C.F., Holliman, J.H., Howell, L.H. and Greenough, J.A., 1997, ApJ, 489, L179.
Whitehouse, S.C. and Bate, M. R., 2006, MNRAS, 367, 32.
Williams J. P., Myers P. C., Wilner D. J. and Di Francesco J., 1999, ApJ, 513, L61.
Vanhala, H.A.T. and Cameron, A.G.W., 1998, ApJ, 508, pp. 291-307.
Vazquez-Semadeni, E., Gonzalez, R.F., Ballesteros-Paredes, J. Gazol, A. and Kim, J., 2008, MNRAS , 390, pp.769-.
Xing, L., 2018, ApJ , 855, pp. 9L–39L.
Table 1  The models, the values of their parameters and resulting configurations.

| Model Number (label) | $V_0/c_0$ ($V_0$ km/s) | $\beta$ | Figure | Configuration                  |
|----------------------|------------------------|---------|--------|--------------------------------|
| 1 (C)                | 0.0 (0.0)              | 1.19    | 3 and 4 | central cluster               |
| 2 (S2)               | 2.0 (0.7)              | 0.1     | 5      | fragmented central region     |
| 3 (S5)               | 5.0 (1.7)              | 0.40    | 6      | a thick shell                 |
| 4 (S10)              | 10.0 (3.4)             | 1.48    | 7      | a shell                       |
| 5 (S20)              | 20.0 (6.8)             | 5.82    | 8      | a thin shell                  |
| 6 (S50)              | 50.0 (17.1)            | 36.2    | 9      | a very thin shell             |
Fig. 1  For the first snapshot of each model, the measured velocity profile against the clump radius for Models C (two curves at times $t/t_{ff}=0$ and $t/t_{ff}=0.299$) and S2–S50, is shown by plots of the (left) velocity magnitude and (right) radial component of the velocity. Velocities are normalized with the initial speed of sound of the clump.

Fig. 2  Time evolution of the peak density $\rho_{max}$ of Models C and S2–S50.
Fig. 3  For the turbulent clump model at time $t/t_{ff} = 0.97$ when the peak density is $\log_{10}(\rho_{\text{max}}/\rho_0) = 16.5$, corresponding to the last snapshot obtained, the region $(-0.1 \times R_0, 0.1 \times R_0)$ of the X-Y midplane of the clump is shown by means of (left) an iso-density plot and (right) a velocity plot.

Fig. 4  For the turbulent clump model at time $t/t_{ff} = 0.299$, when the peak density is $\log_{10}(\rho_{\text{max}}/\rho_0) = 0.23$; this is the moment at which the velocity pulse is activated in models S2-S50, the region $(-0.9 \times R_0, 0.9 \times R_0)$ of the X-Y midplane of the clump is shown by means of (left) an iso-density plot and (right) a velocity plot.
Fig. 5  When the velocity pulse is activated with initial velocity $2c_0$, at time $t/t_{ff} = 0.62$
when the peak density is $\log_{10}(\rho_{\max}/\rho_0) = 13.4$, the region $(-0.3 \times R_0, 0.3 \times R_0)$ of
the x-y midplane of the clump is shown by means of (left) a iso-density plot and (right) a
velocity plot.

Fig. 6  When the velocity pulse is activated with initial velocity $5c_0$, at time $t/t_{ff} = 0.53$
when the peak density is $\log_{10}(\rho_{\max}/\rho_0) = 6.3$, the region $(-0.4 \times R_0, 0.4 \times R_0)$ of
the x-y midplane of the clump is shown by means of (left) a iso-density plot and (right) a
velocity plot.
Fig. 7  When the velocity pulse started at $10c_0$, at time $t/t_{ff} = 0.44$ when the peak density is $\log_{10}(\rho_{\text{max}}/\rho_0) = 6.4$, the region $(-0.4 \times R_0, 0.4 \times R_0)$ of the x-y midplane of the clump is shown by means of (left) a iso-density plot; (right) a velocity plot.

Fig. 8  When the velocity pulse started at $20c_0$, at time $t/t_{ff} = 0.17$ when the peak density is $\log_{10}(\rho_{\text{max}}/\rho_0) = 10$, the region $(-0.4 \times R_0, 0.4 \times R_0)$ of the x-y midplane of the clump is shown by means of (left) a iso-density plot and (right) a velocity plot.
When the velocity pulse started at $50c_0$, at time $t/t_{ff} = 0.01$, when the peak density is $\log_{10}(\rho_{max}/\rho_0) = 3.5$, the region $(-0.9 \times R_0, 0.9 \times R_0)$ of the x-y midplane of the clump is shown by means of (left) a iso-density plot and (right) a velocity plot.

(left) The log of the ratio between the radial density to the average initial density, against the radius of the sphere model normalized with the initial clump radius $R_0$; (right) the mass contained in the dense shell formed at the last snapshot available for each model, shown here in the x-axis.
Fig. 11  For the last snapshot available for each model, the measured velocity profile against the clump radius for Models S2–S50 is shown by plots of the (left) velocity magnitude and (right) radial projection of the velocity. Velocities are normalized with the initial speed of sound of the clump.

Fig. 12  A zoom-in of the outflow region for Model S20 shown in Fig. 8, here at time $0.15 \ t_{\text{ff}}$, when the peak density is $\log_{10} (\rho_{\text{max}}/\rho_0) = 9.3$, and the region is delimited by $(-0.6 \times R_0, 0.6 \times R_0)$ in the $x$-axis and by $(-0.7 \times R_0, -0.2 \times R_0)$ in the $y$-axis.
Fig. 13 On the vertical axis, the distance from the shell of dense gas to the clump centre is shown, given in terms of the radius of the clump. The horizontal dashed line indicates the distance for models included in the iso-density plot shown in Fig 14.
Fig. 14  Iso-density plot of the shock models S2-S20 for a region delimited by $(-0.8 \times R_0, 0.8 \times R_0)$ in the $x$-axis and by $(-0.8 \times R_0, 0.8 \times R_0)$ in the $y$-axis, when the particle distribution reaches a peak density of (a) $\rho_{\text{max}} = 3.6 \times 10^{-20}$ g cm$^{-3}$ at time $t/t_{ff} = 0.58$ for model S2; (b) $\rho_{\text{max}} = 2.5 \times 10^{-19}$ g cm$^{-3}$ at time $t/t_{ff} = 0.65$ for model S5; (c) $\rho_{\text{max}} = 3.5 \times 10^{-17}$ g cm$^{-3}$ at time $t/t_{ff} = 0.56$ for model S10 and (d) $\rho_{\text{max}} = 1.2 \times 10^{-10}$ g cm$^{-3}$ at time $t/t_{ff} = 0.46$ for model S20. These snapshots are chosen to illustrate the models shown in Fig. 13 with a horizontal dashed line.
