Triggered star formation by shocks

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ABSTRACT

Star formation can be triggered by compression from shock waves. In this study, we investigated the interaction of hydrodynamic shocks with Bonnor-Ebert spheres using 3D hydrodynamical simulations with self-gravity. Our simulations indicated that the cloud evolution primarily depends on two parameters: the shock speed and initial cloud radius. The stronger shock can compress the cloud more efficiently, and when the central region becomes gravitationally unstable, a shock triggers the cloud contraction. However, if it is excessively strong, it shreds the cloud more violently and the cloud is destroyed. From simple theoretical considerations, we derived the condition of triggered gravitational collapse, which agreed with the simulation results. Introducing sink particles, we followed the further evolution after star formation. Since stronger shocks tend to shred the cloud material more efficiently, the stronger the shock is, the smaller the final (asymptotic) masses of the stars formed (i.e., sink particles) become. In addition, the shock accelerates the cloud, promoting mixing of shock-accelerated interstellar medium gas. As a result, the separation between the sink particles and the shocked cloud center and their relative speed increase over time. We also investigated the effect of cloud turbulence on shock-cloud interaction. We observed that the cloud turbulence prevents rapid cloud contraction; thus, the turbulent cloud is destroyed more rapidly than the thermally-supported cloud. Therefore, the masses of stars formed become smaller. Our simulations can provide a general guide to the evolutionary process of dense cores and Bok globules impacted by shocks.

Keywords: hydrodynamics — ISM: clouds — methods: numerical — shock waves — stars: formation

1. INTRODUCTION

1.1. Triggered star formation

Galactic star formation is occasionally classified into two main processes. One is “spontaneous star formation,” in which the contraction of molecular clouds and subsequent star formation proceeds without any significant external disturbances. The other is “triggered star formation,” in which external factors promote the compression of molecular clouds, which induces star formation. The external compression is driven by shock waves generated by stellar winds, supernova explosions, cloud-cloud collision, etc. For example, Elmegreen & Lada (1977) suggested that the compressed dense layer between a shock and an ionization front can be gravitationally unstable. Cloud-cloud collisions have been proposed as an important mechanism in the formation of high-mass stars (e.g., Stolte et al. 2008; Furukawa et al. 2009; Wu et al. 2017). There is also increasing observational evidence for star formation triggered by supernovae, ionization.
fronts, cloud-cloud collisions, and other shocks in the interstellar medium (ISM) (e.g., Yokogawa et al. 2003; Ortega et al. 2004; Hester & Desch 2005; Furukawa et al. 2009; Kinoshita et al. 2021).

Thus, triggered star formation can occur when supersonic shocks sweep over clouds. The shock-cloud interaction is a fundamental and important physical phenomenon for star formation. Generally, shock-cloud interactions are highly nonlinear hydrodynamic processes thus numerical simulation is an effective tool to understand these details. Over the past decades, the shock-cloud interaction has been explored by many groups (e.g., Klein et al. 1994; Xu & Stone 1995; Boss 1995; Nakamura et al. 2006; Pittard et al. 2009; Banda-Barragán et al. 2018). Most models assumed the two-dimensional (2D) axial-symmetric geometry. The first three-dimensional (3D) simulations were conducted by Stone & Norman (1992). These simulations demonstrated that cloud destruction occurs faster in 3D because of the rapid growth of hydrodynamic instabilities in 3D. Later, the effects of various physical factors were explored by including turbulence (e.g., Pittard et al. 2009), magnetic fields (e.g., Fragile et al. 2005), and radiative cooling (e.g., Mellema et al. 2002). Some numerical simulations of these studies incorporated self-gravity. These studies revealed the details of triggered star formation by shocks, particularly in the context of the formation of our solar System triggered by a supernova shock (e.g., Boss 1995; Foster & Boss 1996; Vanhala & Cameron 1998; Vanhala & Boss 2002 Boss et al. 2008; Leão et al. 2009; Boss & Keiser (2013); Li et al. 2014; Falle et al. 2017). These previous studies demonstrated that isothermal shocks can trigger the gravitational collapse of stable clouds. Boss & Keiser (2013) observed that faster shocks destroy and disperse the cloud material before its collapse. In contrast, Falle et al. (2017) demonstrated that slower shocks cannot induce collapse. These previous results indicate that only intermediate-speed shocks can trigger gravitational collapse.

Additionally, actual clouds and cores contain turbulent motions. Recently, Banda-Barragán et al. (2018) performed numerical experiments to investigate how cloud turbulence influences the shock-cloud evolution in the absence of self-gravity. They suggested that cloud turbulence results in faster cloud destruction and influences several ISM properties such as cloud porosity. Supersonic turbulence also enhances the acceleration of clouds owing to shocks.

In this study, we used 3D hydrodynamic numerical simulations to study shock-cloud interactions. We considered an isothermal shock interacting with a Bonnor-Ebert sphere. In these simulations, self-gravity and sink particles were included. This initial setup was similar to those of Li et al. (2014) and Falle et al. (2017). Li et al. (2014) considered an application to the formation process of our Sun through a shock-cloud interaction. Thus, their initial conditions were very specific. Falle et al. (2017) investigated the early stages of shock-cloud interactions and derived the condition for the triggered gravitational collapse of stable Bonner-Ebert spheres. Here, we considered more general cases in a wider parameter range (from stable to unstable clouds). The inclusion of sink particles enabled us to follow a much longer evolution of the shock-cloud evolution. We also examined the effects of cloud turbulence on the shock-cloud interaction by including transonic cloud turbulence, which is often observed in the cloud cores in star-forming regions.

In the context of astronomical objects, we envisioned these simulations to represent the interaction of ISM shocks with dense cores and Bok globules in star-forming regions. Although the observed dense cores and Bok globules were not in perfect equilibrium, some observations indicate that the density structures of the dense cores and Bok globules were in reasonable agreement with those of Bonner-Ebert spheres (e.g., Bacmann et al. 2000; Kandori et al. 2005; Alves et al. 2001). In some star-forming regions such as rho Oph and Orion A, the majority of the cores is likely to be pressure-confined (Maruta et al. 2010; Kirk et al. 2017). Therefore, our initial setup of the simulations is expected to represent reasonable conditions that are occurring in the ISM.

This paper is organized as follows. In Section 2, we describe the numerical methods, initial conditions, and simulation models which we employed in this study. In Section 3, we present the numerical results. Thereafter, we discuss interpretations of simulation results in Section 4. We derived a simple analytic condition for triggered gravitational collapse. Finally, we summarize our results and conclusion in Section 5.

2. NUMERICAL METHODS

2.1. Basic Equations and Numerical Code

In this study, the simulations were conducted using Enzo, a magnetohydrodynamics adaptive mesh refinement (AMR) code (Bryan et al. 2014). We used Version 2.6 of the Enzo code in a 3D Cartesian coordinate system \((x, y, z)\). We numerically solved the following hydrodynamic equations for mass, momentum, and energy conservation:

\[\text{http://enzo-project.org}\]
\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla p &= -\rho \nabla \phi,
\end{align*}
\]  
and
\[
\frac{\partial}{\partial t} \left\{ \rho \left( \frac{1}{2} v^2 + \epsilon \right) \right\} + \nabla \cdot \left\{ \rho \mathbf{v} \left( \frac{1}{2} v^2 + h \right) \right\} = -\rho \mathbf{v} \cdot \nabla \phi,
\]
where \( \rho \) is the density, \( \mathbf{v} \) is the velocity, \( p \) is the pressure, \( \epsilon \) is the internal energy, \( h = \epsilon + p/\rho \) is the enthalpy, and \( \phi \) is the gravitational potential. We used the ideal gas law:
\[
p = (\gamma - 1)\rho \epsilon.
\]
\( \phi \) can be determined by solving the following Poisson’s equation:
\[
\nabla^2 \phi = 4\pi G (\rho + \rho_{\text{particle}}),
\]
where \( G \) is the gravitational constant and \( \rho_{\text{particle}} \) is the density of sink particles assigned onto the finest grids by using a second-order cloud-in-cell interpolation technique (Hockney & Eastwood 1988). See Section 2.2.5 for the details of the sink particles.

We assumed a mean molecular weight \( \mu = 2.3 \), and \( \gamma \) was set to 1.00001 for an approximate isothermal assumption. In this study, we considered the purely hydrodynamic problem, ignoring radiative cooling, heating, magnetic fields, and thermal conduction.

The hydrodynamic equations were solved using a Runge Kutta second-order based monotone upstream-centered scheme for conservation laws (MUSCL) (van Leer 1977). The Riemann problem was solved using the Harten-Lax-van Leer (HLL) solver, a two-wave, three-state solver with no resolution of contact waves, while the reconstruction method for the MUSCL solver was a piecewise linear model (PLM). Refer to Bryan et al. (2014) for more details.

### 2.2. Initial conditions

#### 2.2.1. Problem setup

![Schematic of the simulation setup. The cloud is centered at (0, 0, 0). The shock is propagating upwards through the ISM with the velocity \( v_{sh} \). The shocked ISM is indicated in gray.](image)

**Figure 1.** Schematic of the simulation setup. The cloud is centered at (0, 0, 0). The shock is propagating upwards through the ISM with the velocity \( v_{sh} \). The shocked ISM is indicated in gray.
Table 1. Initial simulation parameters

| Parameter | unit | Value | Caption |
|-----------|------|-------|---------|
| $T_{cl}$  | (K)  | 10    | Cloud temperature. |
| $T_{ism}$ | (K)  | $10^3$ | Preshocked ambient ISM temperature. |
| $\rho_c$ | (cm$^{-3}$) | $10^4$ | Central number density of the cloud. |
| $\chi_s$ |   | $10^2$ | Density contrast between the cloud surface and the ambient ISM gas. |
| $c_{cl}$  | (km s$^{-1}$) | 0.19 | Sound speed in the cloud. |
| $c_{ism}$ | (km s$^{-1}$) | 1.9  | Sound speed in the ambient gas. |
| $\xi$     |   | 2.04–14.22 | Dimensionless radius of the cloud. |
| $M_{sh}$  |   | 1.20–7.00 | Mach number of the propagating shock. |
| $\xi_{crit}$ |   | 6.45 | Critical dimensionless radius (see Appendix A). |

Summary of the initial physical parameters.

In the simulations, we considered the interaction between a planar shock and a Bonnor-Ebert sphere initially at equilibrium. Observations have indicated that the density profiles of dense cores and Bok Globules such as B68 can be approximated by that of a Bonnor-Ebert sphere (e.g., Alves et al. 2001). Figure 1 shows the schematic of our simulation setup. The simulation domain was a rectangular prism. The domain length of each side was $8r_{cl}$, $8r_{cl}$, and $16r_{cl}$, for the $x$, $y$, and $z$ directions, respectively, where $r_{cl}$ is the cloud radius. To follow the shock-cloud evolution, we set the side length in the $z$ direction, in which the shock propagates, to be longer than the other two sides ($x$ and $y$). The computational domain was set to $-4r_{cl} \leq x \leq 4r_{cl}$, $-4r_{cl} \leq y \leq 4r_{cl}$, and $-4r_{cl} \leq z \leq 12r_{cl}$. The initial Bonnor-Ebert sphere with a central density $\rho_c$ was placed at the coordinate origin $(0, 0, 0)$, and outside the cloud, we set the ISM gas with the constant density of $\rho_{ism}$. The density contrast of the cloud to the ambient gas at the cloud surface was specified by $\chi_s$:

$$\chi_s = \rho_s/\rho_{ism}$$  \hspace{1cm} (7)

where $\rho_s$ is the cloud surface density. Initially, the cloud had a temperature of $T_{cl}$ and was set in pressure equilibrium with the ambient gas, that is,

$$P_0 = \rho_c c_{cl}^2 = \rho_{ism} c_{ism}^2,$$  \hspace{1cm} (8)

where $P_0$ is the cloud surface pressure, $c_{cl}$ is the sound speed in the cloud, $c_{ism}$ is the sound speed of the ambient gas. Therefore, the temperature of the external ISM was $T_{ism} = \chi_s T_{cl}$.

We set an inflow condition on the bottom plane ($x = -4r_{cl}$) in Figure 1 for a shock. For other boundaries, we adopted an outflow boundary condition. When the simulation began, a planar isothermal shock moved to the positive $z$-direction toward the cloud through the ISM with a Mach number of

$$M_{sh} = \frac{|v_{sh}|}{c_{ism}},$$  \hspace{1cm} (9)

where $v_{sh}$ is the shock velocity.

Table 1 shows the initial simulation parameters. We set the cloud central density and temperature as $\rho_c = 10^4$ cm$^{-3}$ and $T = 10$ K, respectively; and $\chi_s$ was fixed to $\chi_s = 100$, thus the ISM temperature became 1000 K.

2.2.2. Model Parameters

we selected an initially stable cloud of $\xi = 3.22$ ($P_0/P_{crit} = 0.5$) to be our fiducial model. In this case, we applied shocks of $M_{sh} = 1.20, 1.41, 3.15, 4.00, 4.46, 5.00, and 5.64$. These Mach numbers correspond to postshock ambient gas pressure being $\sqrt{2}$, 2, 10, 16, 20, 25, and 32 times greater than those of preshocked gas. In addition to fiducial models, we considered a number of different simulation models with different dimensionless radii and shock Mach numbers, as summarized in Figure 2. Appendix 3 specifies initial parameters of each model numerically. We considered both stable
(\(\xi < 6.45\)) and unstable initial clouds (\(\xi \geq 6.45\)). In stable clouds, we set \(\xi = 2.04, 2.48, 3.22, 4.05, \) and 6.45. In our setting, \(\xi = 1\) corresponded to approximately 0.034 pc (cf. Equation (A2)). These dimensionless radii corresponded to \(P_0 / P_{\text{crit}} = 0.125, 0.25, 0.5, 0.75, \) and 1.0, respectively. In \(\xi > 6.45\) cases, we considered \(\xi = 8.52\) and 14.22. These corresponded to \(\rho_c / \rho_s = 28.08\) (twice the density ratio of \(\xi = 6.45\)) and 100.0, respectively. Although the initial cloud was unstable in the \(\xi > 6.45\) cases, the free-fall time was still significantly longer than the shock arrival time and the cloud crushing time \(t_{\text{cc}}\) (see Appendix B.1). We also discuss the cloud evolution triggered by shocks for \(\xi > 6.45\) cases.

### 2.2.3. Turbulent cloud models

In addition to the aforementioned models, we included pure solenoidal turbulence to the fiducial Bonner-Ebert models where \(\xi = \xi_{\text{crit}}\). A velocity power spectrum of \(v_k^2 \propto k^{-4}\) was added to the gas, where \(k\) is the wavenumber. This power spectrum corresponded to the expected spectrum given by Larson’s law (Larson 1981). The initial amplitude of the turbulence was prescribed by the sonic Mach number

\[
M_{\text{tur}} \equiv \frac{\sigma}{c_s} = 1.0, \tag{10}
\]

where \(\sigma\) is the velocity dispersion. In simulations, initially, we evolved the clouds without shocks for 0.48 Myr to form the turbulent density structures in the clouds. Thereafter, clouds with turbulent densities and velocity structures interacted with shocks. The parameters of these turbulent clouds are indicated in Figure 2 (see also Table 3, No.8).

### 2.2.4. Color variable

Similarly to previous simulations (e.g., Xu & Stone 1995), to follow the evolution of shocked clouds quantitatively, we introduced a Lagrangian tracer variable \(C\), represented by

\[
\left(\frac{\partial \rho C}{\partial t}\right) + \nabla \cdot (\rho C v) = 0. \tag{11}
\]

Initially, we defined \(C = 1\) for the entire cloud and \(C = 0\) for the ambient gas everywhere else. During the shock-cloud evolution, the cloud material mixed with the ambient gas, resulting in regions with \(0 < C < 1\). We used the variable \(C\) to quantify cloud mixing rate as

\[
\frac{m_{\text{mix}}}{m_{\text{cl}}} = \frac{\int_{0.1 < C < 0.9} \rho C dV}{m_{\text{cl}}}, \tag{12}
\]

where \(m_{\text{mix}}\) is the total mass in the zones with \(0.1 < C < 0.9\), and \(m_{\text{cl}}\) is the cloud mass expressed as

\[
m_{\text{cl}} = \int_V \rho C dV. \tag{13}
\]

Equation (11) describes the conservation law of \(m_{\text{cl}}\).

We also defined the cloud living rate as

\[
\frac{m_{\text{live}}}{m_{\text{cl}}} = \frac{\int_{C > 0.9} \rho C dV}{m_{\text{cl}}}, \tag{14}
\]

where \(m_{\text{live}}\) is the total mass in the zones with \(C > 0.9\).

To investigate the cloud motion, we used the mass-weighted averaged cloud position in the z-direction, defined by

\[
\langle z \rangle = \frac{1}{m_{\text{cl}}} \int_V z \rho C dV. \tag{15}
\]

### 2.2.5. AMR and sink particle condition

The simulation domain had a top level root grid of \(256 \times 256 \times 512\) with additional levels of AMR. We used the following two criteria as the AMR condition to follow closely cloud evolution and collapse. In all models, the refinement was permitted until the finest resolution reached \(\Delta x_{\text{min}} \sim 2.0 \times 10^{-4}\) pc.

One AMR criterion was based on \(C\). If the local region had \(C > 0.1\), one level AMR was applied. Using this refinement, in all simulation models, the initial cloud radius was divided into 64 cells. A resolution of 64 zones per cloud radius was sufficient to quantitatively follow the shock-cloud evolution (e.g., Klein et al. 1994; Pittard & Parkin 2016).
The other AMR criterion was the Jeans criterion to prevent spurious numerical fragmentation. Truelove et al. (1997) suggested that four cells per Jeans length are the minimum cells required to prevent spurious numerical fragmentation. We adopted the limit in which the Jeans length does not fall below eight cells: \( \Delta x < \lambda_j / 8 \), where \( \lambda_j = \pi^{1/2} c / (G \rho)^{1/2} \) is the Jeans length. In our simulations, the refinement continued until the density reached the threshold value \( \rho_{th} = 1.5 \times 10^4 \rho_c \), where \( \rho_c \) is the initial cloud central density. That is, \( \Delta x < \lambda_j / 8 \) is satisfied as long as \( \rho < \rho_{th} \) (see Equation (29) in Bryan et al. 2014). Applying the sound speed \( c_{cl} \) in the cloud and \( \rho_{th} \), \( \lambda_j / 8 \) was approximately \( \sim 2.0 \times 10^{-4} \) pc. Therefore, in all models the refinement was permitted until \( \Delta x_{min} \sim 2.0 \times 10^{-4} \) pc. When the local density increased to more than \( \rho_{th} \), instead of creating another AMR level, we used the sink particle technique. With this method, any excess mass in the cell above the \( \rho_{th} \) was transferred to the newly created point particle to avoid artificial fragmentation when the Jeans length decreased further during the collapse. By that time, it was clear that the cloud collapse became unstoppable. We set \( \rho_c \) to \( 10^4 \) cm\(^{-3} \) (see Section 2.2.2) and \( \rho_{th}(= 1.5 \times 10^8 \) cm\(^{-3} \)) is three or four orders of magnitude higher than the density of general molecular cloud cores. For \( \rho < \rho_{th} \), the isothermal approximation was valid (for \( \rho \gg 10^6 \rho_c = 10^{10} \) cm\(^{-3} \), the dense cores become adiabatic). When formed, these particles moved through the grid via gravitational interactions with the surrounding gas and other particles.

![Figure 2](image.png)

**Figure 2.** Values employed for each model. The position of each circle indicates the initial condition, dimensionless radius \( \xi \) of the initial cloud, and Mach number \( M_{sh} \) of the propagating shock. The position of each cross point indicates that of turbulent model. Appendix C also specifies initial parameters of each model numerically.

### 3. Numerical Results

Here, we will provide some numerical results. The clouds with \( \xi = 3.22 \) (\( P_0 / P_{crit} = 0.5 \)) were stable initially. First, as a representative example, we will discuss cloud evolution using the results of \( \xi = 3.22 \) at different Mach numbers. In Appendix E, we provide other dimensionless radii cases. Finally, we will discuss the results of turbulent cloud models.

In all cases, we tracked shock-cloud evolution until 10% of the initial cloud mass exited the simulation box.

#### 3.1. Evolution of maximum density

The maximum density is a good indicator of cloud stability. Figure 3 shows the maximum density normalized to the initial central cloud density as functions of time after a shock arrived at a cloud. Hereafter, in all figures, \( t = 0 \) indicates the time when the shock front first reached the surface of the cloud. The vertical dashed line indicates one free fall time \( t_{ff} = (3\pi/32G\langle \rho_{cl} \rangle)^{1/2} \), where \( \langle \rho_{cl} \rangle \) is the mean density of the initial cloud. The solid lines indicates the cases for which gravitational collapse is triggered by the shocks. The cases in which the clouds did not collapse after shock passage are indicated by dashed lines. Below, we term these two cases “triggered-collapse case” and “no-collapse case” respectively.
One important feature is that only intermediate shocks of $M_{sh}=1.41-4.00$ can trigger cloud contraction. For no-collapse cases, the maximum density increased at the beginning but decreased to lower values after rebounding. For example, for the model with a weak shock of $M_{sh}=1.2$, the maximum density reached $\sim 10\rho_c$ by one cloud free-fall time. However, it gradually decreased with time. For the strong shock of $M_{sh}=5.64$, the maximum density reached $\sim 100\rho_c$ at approximately $t=0.1$ Myr. However, the maximum density subsequently decreased to $\sim 10\rho_c$. Even for $M_{sh}=1.41$, the cloud rebounded once before collapsing at $t=0.43$ Myr (point (1) in Figure 3). In triggered-collapse cases, the rate of density-increase becomes decreased at the beginning. After some time, the rate of density-increase increased and the maximum density reached more than $\rho_{th}$ and sink particles are formed.

### 3.2. Density distribution

As discussed in Section 3.1, the density evolution depends on the Mach number $M_{sh}$. Here, we present density distribution results for four cases: (1) a weak shock with $M_{sh}=1.41$, in which the cloud slowly collapses, (2) an intermediate shock with $M_{sh}=3.15$, in which the cloud rapidly collapses after shock passage, (3) a strong shock with $M_{sh}=5.0$, in which the cloud does not collapse, and (4) a weakest shock with $M_{sh}=1.2$, in which the cloud does not collapse.

#### 3.2.1. Weak shock collapse ($M_{sh}=1.41$)

Figure 4 shows the time evolution of the mass density distribution in the $(x,y)$ plane for $M_{sh}=1.41$. In each panel, we magnify the maximum density point. In addition to the times in Myr, the times in dimensionless units normalized to the cloud crushing time $t_{cc}$ (see Appendix B) are also shown. We derived $t_{cc}$ as $\chi \equiv \langle \rho_{cl} \rangle / \rho_{ism}$. The time evolution of the maximum density are also shown in these panels. As Figure 4 (a) and (b) show, the cloud surface was compressed by the shock. The area surrounded by the white dotted lines indicates the compressed shocked layer formed by shocks propagating in the cloud. At approximately $t=0.43$ Myr, the shock propagating in the cloud from downstream collided with that from upstream, and the density increased dramatically at this collision point (the area enclosed by the white circle in Figure 4 (c)). This phase corresponded to the maximum density rebounding (point (1) in Figure 3). After this rebouding, the higher density region was not formed for a while. At approximately $t=0.66$ Myr, the entire cloud began contracting again and the high density region was formed again. As a result, a sink particle was created at $t=0.74$ Myr. While the gas around the cloud center accreted on the sink particle, as shown in Figure 4 (e), the gas at the cloud surface was shredded gradually by the hydrodynamic instability.

Figure 5 shows the mass per unit velocity and density interval. As shown in Figure 5 (a) and (b), as shocks propagate in the cloud, some shock-compressed gas was accelerated and became denser than the initial central density $\rho_c$. Figure
5 (c) corresponds to the rebounding phase (point (1) in Figure 3). Figure 5 (d) corresponds to a density increasing phase when the maximum density reached the same value as Figure 5 (c) again (point (2) in Figure 3). Comparing the mass per unit velocity and density interval of Figures 5 (c) and (d), the mass fraction contained in the dense part seemed to be larger for Figure 5 (d). By the time of Figure 5 (c), the cloud did not contain sufficient mass to become gravitationally unstable. However, by the time of Figure 5 (d), the central part of the shocked cloud contained more mass such that the gravitational collapse was initiated. After the rebound, the amount of dense gas increased as shown in Figure 5 (e), resulting in collapse.

3.2.2. Intermediate shock collapse ($M_{sh}=3.15$)

Figure 6 is the same as Figure 4 but for $M_{sh}=3.15$. As in the $M_{sh}=1.41$ case, the cloud surface was compressed by the shock and the shocked layer progressed to the cloud center. Unlike for $M_{sh}=1.41$, there was no rebounding phase. A large high-density region was formed, resulting in direct gravitational contraction and the creation of a sink particle at approximately $t = 0.16$ Myr. After the sink particle creation, the cloud around the particle was stripped gradually. Eventually, it had a comet-like structure with the sink as the head and the stripped gas as the tail. Figure 7 shows the mass per unit velocity and density interval similar to Figure 5. As the shock propagated in the cloud, high density gas developed monotonically, resulting in gravitational collapse.

3.2.3. Strong shock no-collapse ($M_{sh}=5.00$)

Figure 8 is the same as Figure 4 but for $M_{sh}=5.00$. As shown in Figure 8 (a) and (b), the cloud surface was compressed by the shock, and the entire cloud contracted but did not collapse. After density rebounding at approximately $t = 0.08$ Myr, the cloud was destroyed and swept downstream of the shock mixing with the ambient gas.

Figure 9 shows the mass per unit velocity and density interval for $M_{sh}=5.00$. As shown in Figure 9 (a) and (b), the high-density gas initially increased. Figure 9 (b) corresponds to density rebounding point for the $M_{sh}=5.00$ case (corresponding to the point (3) in Figure 3). After rebounding, the evolution towards the high-density side stopped. Gradually, gas accelerated and distributed on the low-density side. This indicated that the entire cloud was accelerated by the shock, and cloud was dispersed and flowed at a higher speed downstream. In Figure 9 (b), the central denser cloud material had velocity of approximately 2 km/s, and the lower-density outer regions had higher velocities. While Figure 7 (c) (corresponding to (4) in Figure 3) has the same maximum density as Figure 9 (b), the cloud material had a lower velocity ($\lesssim$ 2.0 km/s). For $M_{sh}=5.00$, a high-density region initially formed, but the cloud accelerated more and dispersed before the gravitational collapse.

3.2.4. Weak shock no-collapse ($M_{sh}=1.20$)

Figure 10 is the same as Figure 4 but for $M_{sh}=1.20$. Similar to other $M_{sh}$ cases, as shown in Figure 10 (a) and (b), the cloud surface was compressed by the shock, and the compressed shocked layer advanced to the cloud center. The maximum density rebounded at approximately $t=0.49$ Myr and decreased gradually.

Figure 11 shows the mass per unit velocity and density interval for $M_{sh}=1.20$. Throughout the simulation times, the high-density regions were not as large as those in higher $M_{sh}$ examples. Comparing Figure 11 (c) and Figure 7 (b), which have a common maximum density (points (5) and (6) in Figure 3), for Figure 11 (c), the cloud mass has a lower distribution on the high density side compared with Figure 7 (b) for $M_{sh}=3.15$. That is, at $M_{sh} = 1.20$, a denser gas region was not sufficiently formed compared with the case of successful collapse. For $M_{sh}=1.20$, after rebounding, the surface of the cloud was gradually stripped toward the downstream shock.

3.3. Mixing and living rates

The top panel in Figure 12 shows the time evolution of the mixing rate defined in Equation (12). The larger the shock Mach number is, the faster the mixing rate increases. For $M_{sh} = 4.46$−5.64, at approximately $t = 0.1$ Myr when the maximum density rebound occurred, the mixing rate exceed 0.2 − 0.3, i.e., 20% − 30% cloud gas mixed with the ambient gas. In contrast, for lower $M_{sh}$ cases, the mixing rate did not become higher than 0.2 − 0.3 even when the cloud rebounded. A similar trend is indicated in the bottom panel in Figure 12, which shows the time evolution of living rate defined in Equation (14). For 4.46−5.64 cases, during rebounding, the living rates were lower $\sim 0.8$, whereas, for lower $M_{sh}$ cases, living rates were higher than $\sim 0.8$ when maximum densities increased dramatically. During the cloud contraction, more gas was removed in the larger $M_{sh}$ cases than in the lower $M_{sh}$ ones.
Figure 4. Enlarged slice of the density distribution in the \((x,y)\) plane centered on the maximum density point, and velocity arrows for \(\xi = 3.22\) and \(M_{\text{sh}} = 1.41\). The region in which the maximum density occurred is shown at the center of the figure. Red points indicate the sink particles. The density evolution as in Figure 3 are indicated on the figures. The area surrounded by the white dotted line in panel (a) and (b) indicate the compressed shocked layer formed by shocks propagating in clouds. The area enclosed by the white circle in panel (c) indicates the part where upstream and downstream shocks collided.

3.4. Evolution of sink particles

For triggered-collapse cases, the evolutions of mass and mass accretion rates of sink particles are shown in Figure 13. The accretion rates gradually decreased by a few orders of magnitude and the mass of sink particles converged asymptotically. The top panel in Figure 13 indicates that the higher the Mach number was, the lower the asympt-
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Figure 5. Mass per unit density and velocity (i.e., $\sqrt{v_x^2 + v_y^2 + v_z^2}$) interval for the $\xi = 3.22$ and $M_{sh} = 1.41$ model. Only gas of $C > 0.1$ region is displayed on this figure. The black vertical line indicates the initial cloud central density $\rho_c$. The blue and red two dashed lines show that the total mass of the gas located to the right of these lines accounted for 50% and 20% of the initial cloud mass, respectively.

The results showed that the asymptotic sink particle mass became. For $M_{sh} = 1.41, 1.99, 3.15$, and 4.00, periods when mass accretion rates were above $10^{-6} M_\odot \text{yr}^{-1}$, were 0.22, 0.18, 0.13, and 0.07 Myr, respectively. The higher the Mach number was, the shorter the time with a high accretion rate was. This trend of accretion timescale would affect the asymptotic sink particle mass.

3.5. Initially turbulent cloud cases

Here, we present results of turbulent cloud models. We followed five models of turbulent ($M_{tub} = 1.00$) clouds with a critical Bonnor-Ebert radius by changing the shock Mach number of $1.41 - 5.64$. Figure 15 shows the time evolution of $\rho_{\text{max}}/\rho_c$, $M_{\text{mix}}/M_{cl}$, $M_{\text{live}}/M_{cl}$, $M_{\text{sink}}/M_{cl}$, and accretion rates of sink particles. Figure 15 (a) indicates that $M_{sh} = 1.41 - 3.15$ shocks induced cloud collapse, whereas relatively stronger $M_{sh} = 4.46$ and 5.64 shocks could not induce cloud collapse. Figure 16 and 17 show the magnified slices of the mass density distribution for $M_{sh} = 3.15$ and 4.46 as in Figure 4. For $M_{sh} = 3.15$, a strongly compressed layer was formed and then the cloud collected and collapsed. In contrast, for $M_{sh} = 4.46$, a strongly compressed layer was formed initially and the cloud was later gradually destroyed by the shock and mixed with the ambient gas. Figure 15 (b) and (c) indicate that the larger the Mach number was, the shorter the mixing timescale with the ambient gas became, resulting in higher living rates. Similar to the non-turbulent models, intermediate shocks induced cloud collapse, whereas excessively strong shocks destroyed entire clouds before the collapse and mixed clouds with ambient gas faster. Figure 15 (d) and (e) show the evolution of mass and mass accretion rates of sink particles. Cross points in Figure 14 shows results of turbulent cloud models. The larger the Mach number, the shorter the span of effective accretion rate, and the lower the asymptotic mass of the sink particle.

To investigate the effect of cloud turbulence on shock-cloud evolution, here, we will compare turbulent cloud models with corresponding non-turbulent models for the same cloud radius and shock Mach number. Figure 18 shows the time evolutions of some physical quantities in both turbulent and non-turbulent models for $\xi = 6.45$ and $M_{sh} = 3.15$. Figure 18 (a) shows the maximum density evolution $\rho_{\text{max}}/\rho_c$. Up to $t \sim 0.2$ Myr, the density evolution in two cases were similar. Thereafter, the turbulent cloud had a slower increase in density. As shown in Appendix D, for the turbulent model, the sink particle was formed by 0.49 Myr after the shock touched the cloud, whereas for the non-turbulent clouds model, it was formed by 0.31 Myr. That is, the turbulent cloud had a slower increase in density and slower
sink particle formation than for the non-turbulent cloud. Figure 18 (b) and (c) show the evolution of mixing rates and living rates. For the turbulent cloud, the living rate declined faster and the mixing rate increased faster than that of non-turbulent cloud. That is, the turbulent cloud mixed faster with the surrounding ambient gas and was destroyed. Figure 18 (d) and (e) show the evolution of sink particle mass and accretion rates. The asymptotic sink particle mass in the turbulent cloud model was lower than non-turbulent counterparts. The accretion rate exceeded $10^{-5}M_\odot$ by $t=0.06$ Myr for the turbulent cloud, whereas this occurs at $t=0.18$ Myr for the non-turbulent cloud. For the turbulent cloud, accretion time was shorter and the asymptotic mass of the sink particle became lower.
Figure 7. As Figure 5 for the $\xi = 3.22$ and $M_{\text{sh}}=3.15$ case.

As above, the turbulence prevented cloud contraction, promoted the destruction of the cloud, and reduced the mass of the formed stars. We can conclude that turbulence in the dense cloud has the effect of suppressing star formation by shocks.
Figure 8. As Figure 5 for $\xi = 3.22$ and $M_{\text{sh}}=5.0$. 
Figure 9. Same as Figure 5 for the $\xi = 3.22$ and $M_{\text{sh}}=5.00$ model.
Figure 10. As Figure 4 for $\xi = 3.22$ and $M_{sh} = 1.20$ model.
Figure 11. As Figure 5 for the $\xi = 3.22$ and $M_{sh}=1.20$ model.
Figure 12. Mixing rate (top) and living rate (bottom) defined in Equations (12) and (14) as functions of time after shocks arrived at the cloud for $\xi = 3.22$. For triggered-collapse cases, the transition is indicated by a solid line. After the time at which the sink particle was introduced, transition is not shown. For no-collapse cases, the transition is represented by a dashed line.
Figure 13. Sink particle mass normalized by the initial cloud mass (top) and mass accretion rate of sink particles (bottom) for the $\xi = 3.22$. 
Figure 14. Formation time and the final mass of sink particles in the initial Mach number vs. cloud radius plane. The position of each scattering point indicates the initial condition as in Figure 2. The colors of points correspond to the time interval from when the shock wave reaches the cloud until the sink particles are introduced. For non-collapse cases, the point color is black. Sizes of points correspond to the asymptotic mass of sink particles. Appendix D also specifies results of simulations numerically.
Figure 15. Time evolution of each physical quantities at different Mach numbers in $\xi=6.45$ $M_{\text{tur}} = 1.0$ (initial cloud is turbulent) models. (a) As in Figure 3, ratio of the maximum density to the initial cloud central density $\rho_{\text{max}} / \rho_c$. (b) As in the top panel of Figure 12, mixing rate defined in Equation (12). (c) As in the bottom panel of Figure 12, living rate defined in Equation (14). (d) As in the top panel of Figure 13, ratio of sink particle mass and initial cloud mass $M_{\text{sink}} / M_{\text{cl}}$. (e) As in the bottom panel of Figure 13, evolution of mass accretion rate of sink particles.
Figure 16. As in Figure 4 for $M_{\text{sh}} = 3.15$, $\xi = 6.45$, and $M_{\text{tur}} = 1.00$ (initial cloud is turbulent).
Figure 17. As in Figure 4 for $M_{\text{sh}} = 4.46$, $\xi = 6.45$, and $M_{\text{tur}} = 1.00$ (initial cloud is turbulent).
Figure 18. Time evolution of each physical quantities in both turbulent and non-turbulent models for $\xi = 6.45$ and $M_{sh} = 3.15$. The solid and dashed-dot lines indicate the results for initially turbulent and non-turbulent clouds, respectively. (a) As in Figure 3, the ratio of the maximum density to the initial cloud central density $\rho_{max}/\rho_c$. (b) As in the top panel of Figure 12, mixing rate defined in Equation (12). (c) As in the bottom panel of Figure 12, living rate defined in Equation (14). (d) As in the top panel of Figure 13, ratio of sink particle mass and initial cloud mass $M_{sink}/M_{cl}$. (e) As in the bottom panel of Figure 13, evolution of mass accretion rate of sink particles.
Figure 19. Mass per unit velocity and density interval for the $\xi = 3.22$ models as in Figure 5. The vertical axis shows the value of the velocity normalized by $v_{\text{sur}} = v_{\text{sh}} \chi^{-1/2}$ (see Equation (B10)). Gases with the color variable $C > 0.99$ are indicated in green, while those of $0.1 < C < 0.99$ are indicated in red. (a) and (b) For $M_{\text{sh}} = 1.20$, at $t = 0.16$ Myr and $t = 0.49$ Myr, respectively. (c) and (d) For $M_{\text{sh}} = 3.15$, at $t = 0.06$ Myr and $t = 0.15$ Myr, respectively. (e) and (f) For $M_{\text{sh}} = 5.00$, at $t = 0.03$ Myr and $t = 0.08$ Myr, respectively. (a), (c), and (e) are the same time when expressed in $t_{\text{cc}}$. (b) and (f) correspond to rebounding phase. (d) corresponds to immediately before the sink particle was formed.

4. DISCUSSION

4.1. Conditions for cloud collapse by shocks

As shown in Figure 14, shocks that are excessively strong or weak cannot induce cloud collapse. This is because excessively strong shocks tend to destroy the cloud through hydrodynamic instabilities and excessively weak shocks do not compress the cloud sufficiently to cause them to become unstable. This implies the existence of parameter windows for cloud collapse. In this subsection, we discuss the conditions for gravitational collapse triggered by shocks.

Figure 19 shows the mass per unit velocity and density interval for the $\xi = 3.22$ models as in Figure 5. The vertical axis shows the value of the velocity normalized by $v_{\text{sur}} = v_{\text{sh}} \chi^{-1/2}$ (see Equation (B10)). Gases with the color variable $C > 0.99$ are indicated in green, while those of $0.1 < C < 0.99$ were shown in red. The panels in the upper row are for the $M_{\text{sh}} = 1.20$ cases corresponding to $t = 0.27 t_{\text{cc}}$. The panels in the lower row correspond to $M_{\text{sh}} = 3.15$ at $t = 0.06$ Myr and $t = 0.15$ Myr, respectively. (a), (c), and (e) are the same time when expressed in $t_{\text{cc}}$. (b) and (f) correspond to rebounding phase. (a) and (b) correspond to rebounding phase at $M_{\text{sh}} = 1.20$, at $t = 0.16$ Myr and $t = 0.49$ Myr, respectively.
and the rebounding phase. For $M_{\text{sh}} = 1.20$, the gas accounting for more than 50% of the mass was compressed almost without being stripped. However, as mentioned in Section 3.2.4, the clouds were not sufficiently compressed to develop gravitational instability. The panels in the middle row are for the $M_{\text{sh}} = 3.15$ cases corresponding to $t = 0.27t_{\text{cc}}$ and immediately before sink particle creation. In panel (c), the distribution is shaped like a horizontal V with the root at $v/v_{\text{sur}} \sim 1$. The gas distributed from the root of V toward the origin of the figure corresponds to the gas compressed by the shock progressing to the center of the cloud. Gas distributed from the base of V to the upper left of the figure corresponds to gas stripped and dissipated by the shock. For $M_{\text{sh}} = 3.15$, the compressed gas became dense, resulting in gravitational collapse. The panels in the lower row are for the $M_{\text{sh}} = 5.00$ cases corresponding to $t = 0.27t_{\text{cc}}$ and the rebounding phase. In panel (e), the distribution is shaped like a V as in panel (c), but the V is wider and more gas is dissipated. As shown in Section 3.2.4, eventually, the entire cloud was destroyed.

Based on these results, two conditions must be satisfied for the cloud to contract. The first condition involves the degree of compression by shocks. For low Mach numbers, most of the gas does not become sufficiently dense and gravitational collapse cannot be induced. It is assumed that for cloud collapse, sufficient compression to make Bonnor-Ebert spheres unstable is required. This condition would determine the lower limit of the Mach number. The second condition involves the destruction of clouds. Even if clouds are strongly compressed, shocks with Mach numbers that are excessively large cause the destruction of entire clouds. For clouds to collapse, the timescale for the development of gravitational instability must be shorter than that of destruction. This condition would determine the upper limit of the Mach number. Hereafter, based on the above two conditions, we will estimate the Mach number parameter window for the cloud collapse.

First, we consider the lower limit of $M_{\text{sh}}$. Considering an isothermal shock with a Mach number $M_{\text{sh}}$, the ambient gas pressure behind the shock is $P_0M_{\text{sh}}^2$.

Considering conditions for a Bonnor-Ebert sphere to become unstable, we expect

$$P_0M_{\text{sh}}^2 \geq P_{\text{crit}},$$

where $P_{\text{crit}}$ is the critical pressure of Bonnor-Ebert sphere (see Equation (A9)). This relation implies

$$M_{\text{sh}} > \left( \frac{1.4c_0^5}{\rho_0G^2m_1^2} \right).$$

(17)

Substituting Equation (A2),(A4), and (A6), we obtain a dimensionless expression:

$$M_{\text{sh}} > (5.6\pi)^{\frac{1}{2}} \left[ \xi \frac{d\psi}{d\xi} \exp\left( -\frac{\psi}{2} \right) \right]^{-1}. \tag{18}$$

Since the right-hand side of Equation (18) is a function of $\xi$, it can also be expressed as a function of $\rho_0/\rho$. Calculating the third degree polynomial regression of the right-hand side of Equation (18) in the range of $2.0 \leq \rho_0/\rho \leq 14.1$, we obtain the approximate equation of lower limit of $M_{\text{sh}}$:

$$M_{\text{low}} \approx 0.96 + 0.34 \left( \frac{\rho_0}{\rho} \right)^{-1} + 2.10 \left( \frac{\rho_0}{\rho} \right)^{-2} + 5.16 \left( \frac{\rho_0}{\rho} \right)^{-3} \left( 2.0 \leq \frac{\rho_0}{\rho} \leq 14.1 \right), \tag{19}$$

where $\rho_0/\rho = 14.1$ corresponds to $\xi = \xi_{\text{crit}}$. When $\rho_0/\rho > 14.1$, a Bonnor-Ebert sphere is unstable.

Next, we consider the upper limit of $M_{\text{sh}}$. Iwasaki & Tsuribe (2008) observed that the timescale of the gravitational instability of isothermal layers bounded by a shock wave with the Mach number $M_{\text{sh}}$ is an order of $t_{\text{ff}}/\sqrt{M_{\text{sh}}}$, where $t_{\text{ff}}$ is the free-fall time scale of the preshock region. In our model, the sum of the timescale on which the shock propagates through the cloud and the timescale on which gravitational instability behind the shock increases is estimated as

$$t_{\text{cc}} + t_{\text{ff}}/\sqrt{M_{\text{sh}}} = t_{\text{cc}} + \left( \frac{3\pi}{32G(\rho_0)M_{\text{sh}}} \right)^{1/2}, \tag{20}$$

where $t_{\text{ff}}$ is the free fall time scale of spherical cloud.

It is known that the timescale of the cloud destruction is in the order of the cloud crushing time $t_{\text{des}} = \alpha t_{\text{cc}}$ (see Appendix B). Previous numerical hydrodynamical simulations indicated that $\alpha \sim 2.5 - 4$ (e.g., Klein et al. 1994;
For clouds to be collapsed by shocks, gravitational instability must increase rapidly within the timescale of cloud destruction $t_{\text{des}}$. Hence, we expect

$$t_{cc} + t_{ff}/\sqrt{M_{\text{sh}}} < t_{\text{des}} = \alpha t_{cc}.$$  

(21)

This implies

$$M_{\text{sh}} < \left[ (\alpha - 1) \frac{32G}{3\pi} \right]^{1/2} \frac{r_{cl}(\rho_{cl})}{c_{\text{ism}}\rho_{\text{ism}}^{1/2}}. \quad \text{(22)}$$

This equation can be rewritten dimensionlessly as

$$M_{\text{sh}} < (\alpha - 1)^2 \frac{72}{3\pi^2} \exp(\psi) \left( \frac{d\psi}{d\xi} \right)^2.$$  

(23)

Calculating the th minus third degree polynomial regression of the right-hand side of Equation (23) in the range of $2 \leq \rho_c/\rho \leq 100$, we obtain the approximate equation of upper limit of $M_{\text{sh}}$:

$$M_{\text{upp}} \approx (\alpha - 1)^2 \left\{ -0.78 \log \left( \frac{\rho_c}{\rho} \right) \right\}^3 + 1.61 \left[ \log \left( \frac{\rho_c}{\rho} \right) \right]^2 + 3.36 \left[ \log \left( \frac{\rho_c}{\rho} \right) \right] + 0.06 \right\} \quad \text{(24)}$$

Figure 20 shows the pressure ratio ($P_0/P_{\text{crit}}$) vs ($M_{\text{sh}}$) parameter space for an initially stable Bonnor-Ebert sphere. The solid line demarcates the Mach number estimate based on Equation (18), above which the cloud will become unstable by the shock. The light gray shaded area shows the upper limit estimate for Mach number based on Equation (23) applying $2.25 < \alpha < 2.50$, above which the cloud will be destroyed by hydrodynamic instabilities before the collapse. In the dark gray region, clouds are expected to be induced to collapse by shocks. Based on simulation results, the red points indicate initial cloud parameter pairs corresponding to eventual collapse, while black points indicate cloud parameter pairs corresponding to predicted non-collapse. We can observe that red points are in dark or light gray regions and black points are outside of the light gray region. Hence, the simulation results are in close agreement with our estimates of conditions. However, the upper limit estimate for Mach numbers has a small range in terms of $\alpha$. This upper limit is derived based on an estimate, and hydro instability is a complex process with uncertainty. It may be difficult to perfectly set an upper limit with a single line. However, the range of $\alpha$ used is not excessively large. The criteria we have derived are useful for crude estimates of stable cloud collapse.

Figure 21 shows the density ratio ($\rho_c/\rho_0$) vs ($M_{\text{sh}}$) parameter space similar to Figure 20 with all parameter pairs shown in Figure 14. For initially unstable clouds (i.e., in the right-side region of the critical density ratio line), when applying smaller $\alpha$ ($\sim 2.0$), results of initially unstable clouds consist with the upper limit estimate. The reason for this gap in $\alpha$ range between stable and unstable clouds is that for unstable clouds, the propagating shock speed estimated using Equation (B10) and actual one are not an exact match. For unstable clouds, the density ratio $\rho_c/\rho_0$ is larger and a density gradient along the radial direction affects the shock velocity propagating in the cloud. Therefore, the timescale for shock propagation and cloud contraction expressed by the left-hand side of Equation (21) is affected, and the $\alpha$ range changes. However, our upper limit estimate is useful for an order discussion. Although the upper limit has some uncertainty for larger unstable clouds, the general tendency of results is consistent with our estimate.

In our calculation, for clouds initially at $\xi > 6.45$, at the time when propagating shock begins to compress clouds, little gravitational collapse is in progress. That is, the density profile of the clouds is almost identical between the initial conditions and when the shocks arrive. We note that for $\xi > 6.45$ unstable clouds, in which collapse has progressed further by the time the shock arrives, shock-cloud evolution may change, and ranges of $M_{\text{upp}}$ may differ from our results.

4.2. Asymptotic mass of sink particles

As shown in Section 3.4, comparing results with the same initial radii, the higher the Mach number of the shock is, the lower the asymptotic sink particle mass becomes and the shorter the accretion time is. This would be because the higher the Mach number is, the faster the shock strips the cloud around sink particles. As shown in Figure 6, the cloud around the sink particle is stripped and mixed with ambient gas. Cloud material is accelerated and displacement of
Figure 20. Conditions on the pressure ratio $P_0/P_{\text{crit}}$ versus Mach number for initially stable clouds. The black solid line indicates the lower limit of Mach number $M_{\text{low}}$ represented by Equation (18). The light gray shaded area indicates the upper limit of Mach number $M_{\text{upp}}$ represented by Equation (23) applying $2.00 < \alpha < 2.50$. The dashed-dot lines show the $M_{\text{upp}}$ applying $\alpha = 2.25$ and 2.5. The dark gray shaded area is the region in which cloud collapse can be induced by a shock. The red and black points indicate initial cloud states for which clouds will collapse or not, respectively (see also Figure 14.)

Figure 21. As Figure 20. Conditions on the density ratio $\rho_c/\rho_0$ versus Mach number for all models. The dashed lines indicate the critical density ratio above which cloud is unstable. The dashed-dot lines indicate the upper limit of the Mach number applying $\alpha = 2.0, 2.25$, and $\alpha = 2.5$.

cloud material and the sink particle expands. Therefore, the accretion timescale would be determined by how rapidly the incoming shock can accelerate and strip accreting clouds from sink particles.

Here, we will quantitatively analyze the moving of stripped clouds and sink particles. We use the $\langle z \rangle$ defined in Equation (15) to analyze the moving of stripped clouds.
Figure 22. (a): Position of sink particles and stripped clouds for $\xi = 3.22$ and $M_{sh} = 3.15$. The dashed line indicates the $\langle z \rangle$ defined by the Equation (15). When the mass of the sink particle is less than 90% of the asymptotic mass, the position of the $z$ coordinate of the sink particle is indicated by the dashed-dot line. Moreover, when it is more than 90% of the asymptotic mass, that is indicated by the solid line. The unit of the shown position is $r_{cl}$ with the origin the position of the center of the initial cloud. The black point indicates the position when the sink particle is created. (b): As (a) for $M_{sh} = 4.00$.

Figure 23. (a): Relative displacement between sink particles and stripped clouds in the $z$-direction for $\xi = 3.22$ and $M_{sh} = 3.15$ and 4.00 while the mass of the sink particle is less than 90% of the asymptotic mass. The unit of the relative displacement is $r_{cl}$. The horizontal line indicates the time after the formation of the sink particle. (b): As (a) for the relative velocity between sink particles and stripped clouds. The unit of the relative velocity is $r_{cl}/$Myr.

Figure 22 shows the $\langle z \rangle$ and position of sink particles in the $z$-direction for $\xi = 3.22$ and $M_{sh} = 3.15$ and 4.00. Displacement of the cloud and sink particle is initially small because of the low mass of sink particles. Subsequently, the sink particle drifts behind and displacement becomes larger because accretion progresses and the sink particle mass increases.

Figure 23 shows the relative displacement and velocity between $\langle z \rangle$ and those of sink particles for $\xi = 3.22$ and $M_{sh} = 3.15$ and 4.00. The higher the Mach number of the shock is, the faster the relative displacement and velocity increase. This trend is also observed for other radii values (see Appendix F). Therefore, relative displacement and velocity of the particle and cloud are determined by the shock speed and affect the timescale of accretion and asymptotic mass.

4.3. Effect of turbulence

Figure 24 shows the mass per unit velocity and density interval as Figure 19 for both turbulent and non-turbulent clouds ($M_{sh} = 3.15$ and $\xi = 6.45$). Figure 24 (a) and (d) are at the same time. Figure 24 (b) and (e) also at the
same time, and Figure 24 (e) corresponds to the time immediately before the creation of the sink particle. Comparing Figure 24 (a) and (d), the cloud mass is less distributed on the high density side on the former compared with the latter. As discussed in Section 3.5, the turbulent cloud has a slower increase in density and a slower sink particle formation than the non-turbulent cloud. This slowness would be due to the effective pressure from turbulence in the cloud. Internal turbulence increases effective cloud pressure to the order of $\sim \rho \sigma^2$. This increased pressure enhances cloud diffusivity and suppresses cloud contraction by the external ram pressure due to a shock. Therefore, turbulence prevents rapid gravitational collapse and high density region is formed slowly.

As shown in Figure 24, throughout the evolution of the turbulent cloud, the distribution of the gas shown in red ($C < 0.99$) differs from that of the non-turbulent cloud. For example, as shown in Figure 24 (d), red and green gas shows near V-shaped distribution, while in Figure 24 (a), red gas shows a fan-like distribution. In other words, more gas is dispersed and mixed with the ambient gas. This trend is consistent with that of Figure 18 (b) and (c). Clouds with a turbulent velocity are more prone to Kelvin-Helmholtz instabilities than their non-turbulent counterparts. Therefore, we can infer that turbulent vortical motions in the clouds diffuse the cloud, and the timescale of the mixture becomes shorter.

Figure 23 shows the relative displacement and velocity between $\langle z \rangle$ and those of sink particles for both turbulent and non-turbulent clouds ($M_{sh} = 3.15$ and $\xi = 6.45$). For the turbulent case, throughout the entire evolution, the relative displacement is greater than that of the non-turbulent case. Most of the time, the relative velocity is also greater for the turbulent case. One reason for this trend is that the cloud with a turbulent velocity is more easily destroyed by the shocks and the gas around the sink particles is stripped faster downstream of the shock. Another reason is that, for the turbulent case, the sink particle is formed later, and by the time mass accretion begins, more gas has been accelerated. Therefore, the asymptotic sink particle mass in the turbulent clouds models is lower than the non-turbulent counterparts.

Comparing No.5 and No.8 models results in Appendix D, the upper limit of the Mach number for cloud collapse differed. In turbulent cloud cases, the upper limit of the Mach number is $3.15 < M_{upp} < 4.46$ whereas for the not turbulent cases, it is $5.64 < M_{upp} < 6.00$. That is, the parameter window for the cloud collapse become narrower for turbulent cloud cases.

Thus, turbulence in the cloud makes triggered star formation by shocks more difficult. Pressure due to turbulence retards cloud contraction and facilitates mixing with the ambient gases. The asymptotic stellar mass decreases. Note that our simulation models did not address magnetic fields. In a realistic ISM, magnetic fields exist and can alter the physical process of the shocked cloud. In this study, we considered purely hydrodynamic cases and investigate the effects of turbulence.
Figure 24. As Figure 19. (a), (b), and (c): For $M_{\text{sh}} = 3.15$ and initially turbulent cloud model at $t=0.16$, 0.31, and 0.49 Myr, respectively. (c) corresponds to immediately before the sink particle is formed. (d) and (e) For $M_{\text{sh}} = 3.15$ and initially no-turbulent fiducial cloud model at $t=0.16$ and 0.31 Myr. (e) corresponds to immediately before the sink particle is formed.

Figure 25. As in Figure 23, relative displacement and velocities between sink particles and stripped clouds. Both turbulent and non-turbulent models for $\xi = 6.45$ and $M_{\text{sh}} = 3.15$ are shown. Solid lines are for initially turbulent cloud cases. Dashed-dot lines are for non-turbulent cloud cases.
4.4. Comparison with observation

4.4.1. Globules toward Orion’s veil bubble

The Extended Orion Nebula (M42) is photoionized by a massive star in the Trapezium cluster, \(\theta^1\) Ori C (e.g., O’Dell 2001; Simón-Díaz et al. 2006). Using the IRAM 30m telescope, Goicoechea et al. (2020) presented \(^{12}\)CO and \(^{13}\)CO \((J = 2 − 1)\) maps of the “Veil bubble” driven by the strong wind emanating from \(\theta^1\) Ori C. They indicated the presence of ten CO “globules” blueshifted from the OMC and embedded in the expanding shell that encloses the bubble. These CO globules are small \((R_g \approx 7100 \text{ AU})\), not massive \((M_g \approx 0.3M_\odot)\) and are moderately dense: \(n_H \approx 4.0 \times 10^4\text{ cm}^{-3}\) (median values of the sample). Goicoechea et al. (2020) assumed that they are either transient objects formed by hydrodynamic instabilities or pre-existing over-dense structures of the original molecular cloud. They are sculpted by the passing shock associated with the expanding shell and by UV radiation from the Trapezium. From the estimated masses of globules, they deduced that these globules will not easily form stars. For some globules, their masses are greater than the Bonnor-Ebert mass (see Equation (A7)) but less than Jeans mass.

We calculated the dimensionless radii and \(M_{\text{sh}}\) of these globules assuming that they are ideal Bonner-Ebert spheres and pressure equilibrium with the ambient gas. We note that our calculations and estimation were simplistic. In calculation, we ignored magnetic fields and turbulence. We also assumed the pre-shocked cloud sphere, but in practice, these globules have been compressed to some extent. The estimation here is only a crude one to investigate the general trend. In our calculation, we adopted estimated globule parameters \((T_{\text{ex}}(\text{CO}), R_g, \text{and } n_H)\) listed in Table 1 in Goicoechea et al. (2020) and expanding shell speed \(v_{\text{sh}} = 13 \text{ km s}^{-1}\), assuming that the initial gas density between the globules surface and surrounding ISM is 10. Figure 26 shows dimensionless radius \(\xi\) versus Mach number parameter spaces. Derived parameter pairs of ten globules are plotted. As in Figure 20, the estimated upper and lower limit of \(M_{\text{sh}}\) for collapse are also shown. Some globules are distributed in the parameter space above the \(M_{\text{low}}\), while all cores are distributed in the parameter space above the \(M_{\text{upp}}\). That is, most globules are strongly compressed and become dense, but they are destroyed by shocks, and star formation activities are limited. This prediction for the future star formation of these globules is consistent with the prediction by Goicoechea et al. (2020).

![Figure 26.](image)

Figure 26. As in Figure 20. Conditions of the dimensionless radius \(\xi\) versus Mach number. Parameter pairs of ten globules toward Orion’s Veil bubble are plotted (Goicoechea et al. 2020). The \# numbers near globules parameter pairs correspond to the numbers shown in Table 1 in Goicoechea et al. (2020). These parameter pairs were calculated using Table 1 values \((T_{\text{ex}}(\text{CO}), R_g, \text{and } n_H)\) and expanding shell speed \(v_{\text{sh}} = 13 \text{ km s}^{-1}\) assuming that the initial gas density between globules and surrounding ISM is 10.
Table 2. Estimated parameters of globules toward Orion’s Veil bubble

| globule | $\xi$ | $M_{sh}$ |
|---------|-------|---------|
| #1      | $1.32\pm0.79$ | $24.9\pm6.99$ |
| #2      | $1.57\pm0.98$ | $21.7\pm6.51$ |
| #3      | $1.21\pm0.68$ | $18.5\pm5.88$ |
| #4      | $1.21\pm0.66$ | $15.4\pm5.14$ |
| #5      | $1.63\pm0.96$ | $10.1\pm3.64$ |
| #6      | $1.03\pm0.61$ | $24.4\pm6.73$ |
| #7      | $0.85\pm0.50$ | $10.1\pm3.65$ |
| #8      | $1.20\pm0.70$ | $11.7\pm4.18$ |
| #9      | $0.54\pm0.32$ | $12.2\pm4.32$ |
| #10     | $1.85\pm1.11$ | $9.0\pm3.33$ |

- $a$ Corresponding to numbers in Table 1 in Goicoechea et al. (2020).
- $b$ Estimated dimensionless radius.
- $c$ Estimated Mach numbers of the propagating shock.

Figure 27. $\Sigma$-PDFs of regions from $\xi = 3.22$ and $M_{sh} = 1.20$, 3.15, and 5.00 cases, respectively, as they evolve in time. For each case, $t = 0.0, 0.3, 0.6, 0.9$, and 1.2 $t_{cc}$ are shown. The $4r_{cl} \times 8r_{cl} \times 16r_{cl}$ box data centered on the initial cloud is shown. The column density is derived assuming that the line of sight is parallel to the $x$-axis (see Figure 1). The vertical red dashed line shows the amount of integration of $\rho_s$ in the line of sight direction.

4.4.2. Mass surface density PDFs

Figure 27 shows time evolution of column density $\Sigma$-PDFs for $M_{sh} = 1.20, 3.15$, and 5.00 for $\xi = 3.22$. These are the distribution of the column density when looking at the $4r_{cl} \times 8r_{cl} \times 16r_{cl}$ box data centered on the initial cloud from the $x$-axis direction. $M_{sh} = 3.15$ corresponds to the triggered collapse case, while $M_{sh} = 1.20$ and 3.15 correspond to the no-collapse cases. Although a sink particle is formed for $M_{sh} = 3.15$, only gas is included in this figure.

For $M_{sh} = 1.20$, until approximately $t = 0.9t_{cc}$ the PDFs exhibit a broadening distribution, with rebounding occurring at approximately $t = 1.2t_{cc}$. The distribution does not exceed $10^{-1} g \cdot cm^{-2}$ and is not as broad as the other two PDFs. For $M_{sh} = 3.15$, until approximately $t = 0.6t_{cc}$ PDFs exhibit a broadening of distribution. The foot of high-density side increases to $\sim 10^{-1} g \cdot cm^{-2}$. After the sink particle creation at $t \sim 0.7t_{cc}$, the PDFs rebound. For $M_{sh} = 5.00$, the distribution also becomes wider and the foot of the high-density side extends above $\sim 10^{-1} g \cdot cm^{-2}$. Compared with the other two PDFs, the value of the vertical axis $p(N_H)$ is generally smaller and the total amount of gas above $\int_0^{2r_{cl}} \rho_s dl$ is smaller. After approximately $t = 0.9t_{cc}$, the distribution rebounds.

Depending on Mach numbers, each PDF exhibits different characteristics. However, since PDFs evolve over time, it is difficult to distinguish the presence or absence of collapse from only the $\Sigma$-PDFs. The distribution tail extending to the high-density side does not necessarily indicate a triggered collapse, and PDFs of observational data should be addressed carefully.
5. CONCLUSION

We studied the shock-cloud interaction using 3D hydrodynamical simulations with self-gravity and sink particles. We demonstrated that the evolution of the shocked clouds strongly depends on shock speeds and cloud radii. If the Mach number of the shock is excessively low, the shock cannot compress the cloud sufficiently to induce cloud collapse and the cloud is destroyed gradually. While, if the Mach number of the shock is excessively high, the shock destroys clouds through the hydrodynamical instability of the cloud surface before cloud collapse. Only an intermediate Mach number shock can trigger cloud collapse. In addition, even when clouds collapse, there are differences in cloud evolution such as the presence or absence of rebounding. We discuss that constraints of the Mach number for the collapse can be expressed as functions of dimensionless radii. The lower limit of the Mach number can be got by comparing the critical pressure of Bonnor-Ebert sphere and postshock pressure of ambient gas. The upper limit of the Mach number can be got by comparing the timescale of cloud collapse and cloud destruction.

For the case in which cloud can collapse, the higher the Mach number of the shock is, the lower the asymptotic mass of the formed sink particle becomes. This is because higher-Mach-number shocks strip cloud gas around the sink particle faster and make effective accretion time shorter. We showed that the higher the Mach number of shock is, the faster the relative velocity and position increase.

We also address cases in which initial clouds have turbulent velocity fields. We observed that turbulent clouds have the same trends as non-turbulent counterparts on evolution differences depending on Mach number. Some shocks can trigger cloud collapse, whereas excessively strong shocks destroy clouds faster and cannot induce cloud collapse. The turbulence itself suppresses cloud contraction and decreases formed asymptotic sink particles mass.

These simulation results provide a general guide to the evolutionary process of dense cores or Bok globules impacted by shocks due to supernovae, stellar winds, and ionization fronts.

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Computations described in this work were performed using the publicly-available Enzo code (http://enzo-project.org), which is the product of a collaborative effort of many independent scientists from numerous institutions around the world. Their commitment to open science has helped make this work possible.

Software: Enzo (Bryan et al. 2014), Yt (Turk et al. 2011)

APPENDIX

A. BONNOR-EBERT CLOUDS

The Bonnor-Ebert sphere is an isothermal gas sphere remaining in hydrostatic equilibrium (Ebert 1955; Bonnor 1956). The equation of hydrostatic equilibrium can be nondimensionalized to obtain the isothermal Lane-Emden equation (Chandrasekhar 1967):

\[
\frac{1}{\xi^2} \frac{d}{d\xi} \left( \xi^2 \frac{d\psi}{d\xi} \right) = \exp(-\psi),
\]

(A1)

where \( \xi \) is the dimensionless radius, by putting

\[
\xi = \sqrt{\frac{4\pi G \rho_c}{c_{cl}^2}} r,
\]

(A2)

and

\[
\rho = \rho_c \exp(-\psi),
\]

(A4)

where \( \rho_c \) is the central density of sphere, \( c_{cl} \) is the thermal speed of sound, \( r \) is the characteristic radius of the cloud.
We can obtain a numerical solution with the boundary conditions

\[ \psi(0) = \frac{d\psi(0)}{d\xi} = 0. \]  

(A5)

Figure 28. Density profile of the Bonnor-Ebert sphere. The abscissa is the dimensionless radius \( \xi \), and the ordinate is the density ratio \( \rho/\rho_c \). The vertical dashed line indicates the critical dimensionless radius \( (\xi_{\text{crit}} = 6.45) \), above which the Bonnor-Ebert sphere is unstable.

Figure 28 shows the radial density profile of the Bonnor-Ebert sphere (i.e., the numerical solution of Equation A1 and A5).

The total mass within the Bonnor-Ebert sphere is expressed as

\[ m_{\text{cloud}} = 4\pi \rho_c \left( \frac{c^2}{4\pi G \rho_c} \right)^{3/2} \xi^2 \frac{d\psi}{d\xi}. \]  

(A6)

The Bonnor-Ebert sphere is unstable when its dimensionless radius exceeds the critical dimensionless radius of \( \xi_{\text{crit}} = 6.45 \). The Bonnor-Ebert critical mass and pressure corresponding to this critical value are, respectively,

\[ m_{\text{crit}} = 1.18 \frac{c_s^4}{G^{3/2} P_0^{1/2}}, \]  

(A7)

and

\[ P_{\text{crit}} = 1.40 \frac{c_s^8}{G^3 m_{\text{cloud}}}. \]  

(A8)

(B. TIMESALES

Here, we define several important characteristic timescales to discuss the evolution of shocked clouds.

B.1. Cloud crushing time

Consider a uniform spherical cloud of radius \( r_{\text{cl}} \) and density \( \rho_0 \) in pressure equilibrium with an ambient gas of density \( \rho_{\text{ism}} \). We focus on the case in which a planar shock of velocity \( v_{\text{sh}} \) interacts with an isothermal cloud without magnetic fields. When a shock encounters a cloud, an overpressure region and shock will be driven into the cloud. If the shock
is strong, the post-shock pressure is approximately $\rho_{\text{ism}} v_{\text{sh}}^2$. The post-shock pressure in the cloud is of the order $\rho_0 v_{\text{cl}}^2$, where $v_{\text{cl}}$ is the velocity of the shock in the cloud. Assuming that these two pressures must be comparable, we obtain

$$v_{\text{cl}} \sim \left( \frac{\rho_0}{\rho_{\text{ism}}} \right)^{1/2} v_{\text{sh}} \chi^{-1/2}, \quad (B10)$$

where $\chi$ is the ratio of cloud density to ambient gas density. The cloud crushing time $t_{cc}$ is the time for the shock to pass across the cloud:

$$t_{cc} = \frac{r_{\text{cl}}}{v_{\text{cl}}} \sim \frac{\chi^{1/2} r_{\text{cl}}}{v_{\text{sh}}}. \quad (B11)$$

This is the important time scale for the evolution of the shocked cloud. In this study, we used $t_{cc}$ as $\chi = \langle \rho_{\text{cl}} \rangle / \rho_{\text{ism}}$.

### B.2. Drag timescale

The shock wave accelerates the cloud until it is comoving with the postshock ambient gas. Let $v_c$ be the mean velocity of the cloud, $v_p$ the velocity of the postshock ambient gas, and $v_r = |v_p - v_c|$ the magnitude of the velocity of the cloud relative to velocity of the postshock ambient gas. If we consider the momentum transfer from an ambient gas with cross-section $\pi r_{\text{cl}}^2$, the equation of motion of the cloud is

$$M_{\text{cl}} \frac{dv_r}{dt} = -(\pi r_{\text{cl}}^2) \rho_{\text{ism}} v_r^2; \quad (B12)$$

where $M_{\text{cl}}$ is the cloud mass. This equation yields the characteristic drag timescale $t_{\text{drag}}$ as

$$t_{\text{drag}} \sim \chi^{1/2} t_{cc}. \quad (B13)$$

### B.3. Destruction timescale

After the shock wave has swept over the cloud, the shocked cloud is subject to Kelvin-Helmholtz and Rayleigh-Taylor instabilities. For $\chi \gg 1$, the time-scale for growth of the Kelvin-Helmholtz instability is $t_{KH} = \chi^{1/2} / k v_{\text{rel}}$ (Chandrasekhar 1961), where $k$ is the wave-number of perturbations, and $v_{\text{rel}}$ is the relative velocity between the post-shock ambient gas and the cloud. Since the clouds accelerate rather slowly, $v_{\text{rel}}$ is approximately equal to the velocity behind the shock $v_p = v_{\text{sh}}(1 - 1/M^2)$. Thus, the time-scale for growth of the Kelvin-Helmholtz instability is comparable to the cloud crushing time $t_{cc}$:

$$t_{KH} \sim \frac{t_{cc}}{kr_{\text{cl}}}. \quad (B14)$$

The shortest wavelengths have the fastest growth, but wavelengths corresponding to $kr_{\text{cl}} \sim 1$ are most disruptive.

The drag timescale results in an acceleration $g \sim v_{\text{sh}} / t_{\text{drag}} \sim r_{\text{cl}} / t_{cc}^2$, corresponding to a growth timescale of Rayleigh-Taylor instabilities given by $t_{RT} \simeq (g k)^{-1/2}$ (Chandrasekhar 1961). Thus, the Rayleigh-Taylor growth timescale is also comparable to the cloud crushing time:

$$t_{RT} \sim \frac{t_{cc}}{(kr_{\text{cl}})^{1/2}}. \quad (B15)$$

These timescales for instability suggest that a cloud will be destroyed in a time of the order of the cloud crushing time. Previous studies have shown that the time-scale for cloud destruction is indeed in the order of $t_{cc}$ (e.g., Klein et al. 1994; Nakamura et al. 2006).

### C. VALUES EMPLOYED FOR EACH MODEL

Table 3 specifies the values employed for each model.

### D. SIMULATION RESULTS

Table 4 specifies results of simulations numerically.
| No. | ξ<sup>a</sup> | ξ/ξ<sub>crit</sub><sup>c</sup> | r<sub>cl</sub><sup>d</sup> | P<sub>0</sub>/P<sub>crit</sub><sup>e</sup> | ρ<sub>c</sub>/ρ<sub>s</sub><sup>f</sup> | M<sub>cl</sub><sup>g</sup> | M<sub>sh</sub><sup>h</sup> | v<sub>sh</sub><sup>i</sup> |
|-----|---------|----------------|----------|----------------|-----------------|--------|--------|--------|
| 1   | 2.04    | 0.31            | 0.07     | 0.125          | 1.78            | 0.56   | 1.41   | 2.67   |
|     |         |                 |          |                |                 |        |        |        |
|     |         |                 |          |                |                 |        |        |        |
|     |         |                 |          |                |                 |        |        |        |
| 2   | 2.48    | 0.38            | 0.08     | 0.25           | 2.22            | 0.89   | 1.20   | 2.27   |
|     |         |                 |          |                |                 |        |        |        |
|     |         |                 |          |                |                 |        |        |        |
| 3   | 3.22    | 0.5             | 0.11     | 0.5            | 3.24            | 1.52   | 1.20   | 2.27   |
|     |         |                 |          |                |                 |        |        |        |
|     |         |                 |          |                |                 |        |        |        |
| 4   | 4.05    | 0.63            | 0.14     | 0.75           | 4.94            | 2.31   | 1.20   | 2.27   |
|     |         |                 |          |                |                 |        |        |        |
|     |         |                 |          |                |                 |        |        |        |
| 5   | 6.45    | 1.00            | 0.22     | 1.00           | 14.10           | 4.48   | 3.15   | 5.97   |
|     |         |                 |          |                |                 |        |        |        |
|     |         |                 |          |                |                 |        |        |        |
| 6   | 8.52    | 1.32            | 0.29     | —              | 28.08           | 6.13   | 5.64   | 10.68  |
|     |         |                 |          |                |                 |        |        |        |
|     |         |                 |          |                |                 |        |        |        |
| 7   | 14.22   | 2.20            | 0.49     | —              | 100.00          | 9.78   | 6.00   | 11.37  |
|     |         |                 |          |                |                 |        |        |        |
|     |         |                 |          |                |                 |        |        |        |
| 8   | 6.45    | 1.00            | 0.22     | 1.00           | 14.10           | 4.48   | 1.41   | 2.67   |
|     |         |                 |          |                |                 |        |        |        |
|     |         |                 |          |                |                 |        |        |        |

No.1–7: Simulation values employed for non-turbulent models. No.8: Values employed for turbulent models.

<sup>a</sup> ID of the initial cloud condition.
<sup>b</sup> Dimensionless radius of the Bonnor-Ebert sphere.
<sup>c</sup> Ratio of the dimensionless radius ξ to the critical dimensionless radius ξ<sub>crit</sub>.
<sup>d</sup> Radius of the Bonnor-Ebert sphere (pc).
<sup>e</sup> Ratio of the external pressure P<sub>0</sub> to the critical pressure P<sub>crit</sub>. If the initial cloud is unstable (ξ > 6.45), the value is not shown.
<sup>f</sup> Ratio of cloud central density ρ<sub>c</sub> and cloud surface density ρ<sub>s</sub>.
<sup>g</sup> Mass of the initial cloud (M⊙).
<sup>h</sup> Mach number of the propagating shock.
<sup>i</sup> Propagating shock speed (km s<sup>−1</sup>).
## Table 4. Simulation results

| No $^a$ | $\xi^b$ | $M_{sh}^c$ | $t_{sink}^d$ | $M_{sink}^e$ |
|---------|---------|------------|--------------|--------------|
| 1       | 2.04    | 1.41       | —            | —            |
|         |         | 1.99       | —            | —            |
|         |         | 2.39       | —            | —            |
|         |         | 3.15       | —            | —            |
| 2       | 2.48    | 1.20       | —            | —            |
|         |         | 1.41       | —            | —            |
|         |         | 1.99       | 0.32         | 0.71         |
|         |         | 2.39       | —            | —            |
|         |         | 3.15       | —            | —            |
| 3       | 3.22    | 1.20       | —            | —            |
|         |         | 1.41       | 0.74         | 1.35         |
|         |         | 1.99       | 0.36         | 1.24         |
|         |         | 3.15       | 0.15         | 0.95         |
|         |         | 4.00       | 0.12         | 0.66         |
|         |         | 4.46       | —            | —            |
|         |         | 5.00       | —            | —            |
|         |         | 5.64       | —            | —            |
| 4       | 4.05    | 1.20       | 1.14         | 1.49         |
|         |         | 4.46       | 0.13         | 1.25         |
|         |         | 5.00       | 0.12         | 0.94         |
|         |         | 5.64       | —            | —            |
| 5       | 6.45    | 3.15       | 0.31         | 4.11         |
|         |         | 5.64       | 0.18         | 0.86         |
|         |         | 6.00       | —            | —            |
|         |         | 7.00       | —            | —            |
| 6       | 8.52    | 5.64       | 0.22         | 1.93         |
|         |         | 6.00       | —            | —            |
|         |         | 7.00       | —            | —            |
| 7       | 14.22   | 6.00       | 0.36         | 1.23         |
|         |         | 7.00       | —            | —            |
| 8       | 6.45    | 1.41       | 1.94         | 3.21         |
|         |         | 1.99       | 0.93         | 2.87         |
|         |         | 3.15       | 0.49         | 2.05         |
|         |         | 4.46       | —            | —            |
|         |         | 5.64       | —            | —            |

$^a$ ID of the initial cloud condition.

$^b$ Dimensionless radius of the Bonnor-Ebert sphere.

$^c$ Mach number of the propagating shock.

$^d$ Time interval from when the shock wave reaches the cloud until the sink particles are introduced (Myr). If the sink particles is not formed, the value is not shown.

$^e$ Asymptotic mass of sink particles ($M_\odot$). If the sink particles is not formed, the value is not shown.
E. RESULTS OF DIFFERENT DIMENSIONLESS RADIi MODELS

In this appendix, we show results of cases with different dimensionless radii. Figure 29 shows the evolution of density ratio $\rho_{\text{max}}/\rho_c$ at different dimensionless radius. For $\xi=3.22$, the density evolution depends on $M_{\text{sh}}$. For triggered-collapse cases, the maximum density increases monotonically or after rebounding (e.g., $\xi=4.05$ and $M_{\text{sh}}=1.20$ case), inducing gravitational collapse. Moreover, when $M_{\text{sh}}$ is lower or higher, the maximum density increases at the beginning but decreases to lower values after rebounding without cloud collapse. For $\xi=4.05$, all of them correspond to no-collapse cases.

Figure 30 and 31 show evolution of the mixing and living rates. For $\xi=3.22$, the larger the Mach number, the shorter the time scale of the mixture with the ambient gas. That is, in all cases, the higher the propagating shock velocity, the faster the destruction of the cloud progress.

Figure 32 and 33 show the evolution of sink particles mass and accretion rates. Figure 14 shows the results of each model. From $\xi=4.05$ or $\xi=6.45$, we can conclude that the higher the Mach number, the slower the sink particle formation begins and the lower asymptotic sink particles mass. This trend is also the same for $\xi=3.22$.

F. MOVING OF SINK PARTICLES AND STRIPPED CLOUDS

Figure 34 shows the relative displacement and velocity between sink particles and stripped clouds for $\xi=4.05$ and $M_{\text{sh}}=1.20, 4.46, \text{and } 5.00$ cases.
Figure 29. Ratio of the maximum density to the initial cloud central density $\rho_{\text{max}}/\rho_c$ as functions of time at different shock Mach numbers. If a sink particle is introduced during the shock-cloud evolution, the transition is represented by a solid line; otherwise, it is represented by a dashed line. The vertical dashed line indicates the free fall time $t_f$. 

Figure 30. Mixing rate defined in Equation (12) as functions of time after shocks arrive at a cloud at different shock Mach numbers. If a sink particle is introduced during the shock-cloud evolution, the transition is represented by a solid line. After the time at which a sink particle is introduced, the transition is not shown. In cases in which a sink particle is not introduced, the transition is represented by a dashed line.
Figure 31. Living rate defined in Equation 14 as functions of time after shocks arrive at a cloud at different shock Mach numbers. If a sink particle is introduced during the shock-cloud evolution, the transition is represented by a solid line. After the time at which sink particle is introduced, the transition is not shown. In cases in which a sink particle is not introduced, the transition is represented by a dashed line.
Figure 32. Ratio of sink particle mass to initial cloud mass $M_{\text{sink}}/M_{\text{cl}}$ as functions of time after shocks arrive at different shock Mach numbers.
Figure 33. Evolution of the mass accretion rate of sink particles.

Figure 34. As in Figure 23 for $\xi = 4.05$ and $M_{sh} = 1.20, 4.46,$ and $5.00.$
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