Formation of filaments and dense cores during molecular clouds collision

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Abstract. The paper presents the results of mathematical modeling of the collision process of two molecular clouds (MC). The density distribution over the radius of the MC is modeled by various laws, the density in the center varies. The forces of gravity, thermal conductivity and radiative losses are not taken into account. The processes of deformation, fragmentation and the formation of superdense regions that occurs during the collision of molecular clouds are analyzed. Visualization of the calculation results made it possible to find the features of the emerging flow the formation of vortices, filaments, and superdense nuclei in molecular clouds.

1. Introduction

A large number of works have been devoted to the study of the behavior of molecular dust clouds and their role in the formation of stars. In pioneering works [1, 2], the processes of interaction of flows with various inhomogeneities were analytically studied. Issues related to the influence of external flows on the properties of inhomogeneous regions were studied.

As computing power increased, work appeared in which the inclusion of gravity and the influence of magnetic fields were added. In the papers [3] - [16], the problem of the interaction of the flow of matter and shock waves with a single MC was investigated. These studies were carried out in one-dimensional and two-dimensional formulations.

In the papers [17]-[21] two and three-dimensional formulations of the problem were considered. In these and in a number of other studies, it became possible to identify complex interactions that arise during the interaction of strong shock waves with molecular dust clouds. The appearance of the Rayleigh-Taylor instability, the entrainment of matter (ablation) during the formation of a turbulent flow and radiative cooling of the cloud substance are studied.

In [18] a single-phase gas model that accurately reflects the physical picture of the flow was used. In the calculations, it was assumed that the unperturbed interstellar matter (ISM) consists of relatively warm matter (∼ 10⁴ K) and small nonuniformly distributed cold clouds (∼ 10² K), which have a high density [13], [17], [22]. Initially, the clouds are in dynamic equilibrium with the background gas [18].

This paper discusses the processes of interaction of two molecular clouds, with different gas-dynamic characteristics. The process of the emerging hypersonic gas-dynamic flow is simulated and the interaction of the processes of compression, fragmentation and the formation of turbulent flows in the clouds and the environment are analyzed.
To carry out the calculations, a parallel algorithm for solving the problems of non-stationary gas dynamics [21] was developed, which was tested in detail when solving the problem of the interaction of an incident shock wave with a region of lower density.

To speed up the calculations, OpenMP technology was used. A parallel code based on high-resolution difference schemes was developed. The code solves three-dimensional Euler equations for a compressible gas. To improve the quality of the parallel code, Intel V Tune Amplifier XE was used.

2. Formulation of the problem
The interstellar medium consists of a relatively warm matter $\sim 10^4K$. There is a molecular cloud in the ISM, the density is much higher than the density of the ISM. The temperature in the molecular cloud is lower than the temperature of the ISM $T_{\text{cloud}} \sim 10^2K$. At the initial moment the molecular clouds are in contact with each other. Inside each molecular cloud, a radial density distribution is given. In fig. (1) is a schematic representation of the initial moment of impact. We use a single-phase gas model.

Initially, the cloud is in dynamic equilibrium with the background gas. The thermal conductivity and radiation losses during the interaction can be neglected. The work uses the equation of state of an ideal gas with $\gamma = 5/3$.

ISM density is $\rho_a = 2.15 \times 10^{-25} \text{g/cm}^3$, temperature $T_a = 10^4K$, $u_a = 0.0$. Cloud’s density is $\rho_c = 1.075 \times 10^{-22}\text{g/cm}^3$, temperature $T_c = 100K$, Mutual impact speeds ranged from $\pm 2 \text{ km/s}$ to $\pm 15 \text{ km/s}$. The collision time of two MCs is approximately equal to one million years.

3. Governing equations

3.1. Governing Equations
The gas dynamic process computations in complex problems are not the only factors requiring high performance computers to be used. Additional intensive computations are required, they being used to account for the effects of gravitational and magnetic fields, viscosity, heat conductivity, etc. The time spent for the additional computations by far exceeds the time of gas dynamic phase computations [25], [28].

The problems being solved consider the flows of ideal compressible gas in nonsteady definition. Viscosity and heat conductivity effects on mass transfer are ignored. The system of conservation laws of mass, momentum, and energy in 3-D Cartesian coordinate system with self-gravitation taken into account can be written in the following way:

$$\frac{\partial Q}{\partial t} + \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z} = S$$

(1)
where quantity $\mathbf{Q} = (\rho; \rho u; \rho v; \rho w; \rho E)^T$ is the state vector, the components of which are conservative variables – densities of mass, momentum and total energy.

Numerical flux $\mathbf{F}_x$, source term and gravity vectors are written as follows:

$$
\mathbf{F}_x = (\rho u; \rho u^2 + P; \rho u v; \rho u w; \rho u E + u P)^T, \\
\mathbf{S} = (0; \rho g_x; \rho g_y; \rho g_z; \rho g \cdot \mathbf{v})^T, \\
\mathbf{g} = (g_x; g_y; g_z)^T = -\nabla \Phi.
$$

In the above equations $\rho$ is density, $\mathbf{v}$ is velocity, $g$ is gravity, $P$ is pressure, $E$ is total energy. The vectors $\mathbf{F}_y, \mathbf{F}_z$ can be written similarly. These equations calculate gravitational potential $\Phi$ with the solution of Poisson equation taken into account:

$$
\nabla^2 \Phi = 4\pi G.
$$

To close the system of equations the equation of state for ideal gas is used in the following form:

$$
P = \rho(\gamma - 1)[E - 1/2(u^2 + v^2 + w^2)],
$$

where $\gamma$ is the ratio of heat capacities.

Initially the molecular clouds show a thermodynamic balance with the environment [28]. Heat conduction and radiation losses are ignored in computations [20]. The equation of state for adiabatic gas is used with $\gamma = 5/3$. The density of interstellar gas is used with $\gamma = 5/3$. The density of interstellar medium is taken equal to $2.15 \times 10^{-25} g/cm^3$, the temperature $T=10000$ K, $u=0$. The density of MC gas is equal to $\rho_a = 1.075 \times 10^{-22} g/cm^3$, the temperature $T=100$ K.

### 3.2. Non-Dimensional Procedure

Numerical computations are done with the minimum accuracy loss if initial values of design quantities range from $\pm 1$. But the density of interstellar media, the density beyond the shock wave front and in MCs have the quantities of approximately $10^{-25}$, the values of temperature and velocity have the quantities of approximately $10^5$. The use of such magnitudes in computations results in significant loss of computation accuracy. The research uses nondimensionalization to have the values of all the quantities in the range specified. This requires each function used in the problem definition to be presented as follows: $f = f_0 f'$, where $f'$ is a dimensionless function and $f_0$ is a dimension factor which can help nondimensionalize the quantities used in computations [26]. The system of equations written in a dimensionless form gives a number of dimensionless fixed factors as Reynolds number, Euler number, etc.

The quantities describing the interstellar medium are used as nondimensionalizing multiplying factors. For example ISM density is $\rho_0 = 2.15 \times 10^{-25} g/cm^3$, temperature $T_0 = 10^4 K$, $u_0 = 0.0$. Let us nondimensionalize the system of equations (1-4). The dimension theory provides that there are only four quantities among all dimensional ones which have an independent dimension. If nondimensionalized values are substituted in the system of equations (1-4), and the required transformations are done, we will have a dimensionless system of equations, with the form of the system not changing. After completing computations we can go back to dimensional quantities.

For a good resolution of the processes occurring in the MC, it is necessary that the radius of the cloud should be at least 128 calculated cells. The size of the difference grid was chosen from these considerations; the main calculations were carried out on a grid with dimensions of $1024 \times 1024 \times 1024$.

### 3.3. Initial and boundary conditions

The calculated area is presented by parallelepiped with sizes $1024 \times 1024 \times 1024$. The density radial distribution formulas for clouds $C_1$ and $C_2$ are the following:

$$
\rho(r) = \rho_{ism} + \frac{\rho_{cl} - \rho_{ism}}{1 + (r/R_{cl})^{2.7128}},
$$

where quantity $Q = (\rho; \rho u; \rho v; \rho w; \rho E)^T$ is the state vector, the components of which are conservative variables – densities of mass, momentum and total energy.
\[ \rho(r) = \rho_{ism}\left(\chi + \frac{\alpha}{\alpha + 1}(1 - \chi)\right), \]  

(6)

where \( \chi = \frac{\rho_{cl}}{\rho_{ism}} \) – density contrast.

Form factor \( \alpha \) in (6) can be calculated by formula:

\[ \alpha = \exp\left\{\min[20,0,10 \cdot \left(\frac{r}{R_{cl}}\right)^2 - 1]\right\}. \]

(7)

Several parameters in these formulas controlling the steepness of clouds border were changed to improve density smoothing. Boundary conditions at all boundaries are free outflow conditions.

4. Numerical methods

In this paper we use the schemes of type TVD. This class of schemes is characterised by usage of non-linear monotonicity condition. Such condition permits one to limit appearance of new maximums and minimums which inevitably arise in the high order accuracy schemes. Monotonous against-streaming scheme for conservative laws, used in calculations, is the modification of the first order monotonous against-streaming scheme. This scheme fits very well to the three-dimensional Euler equations solution.

The steps by time are calculated with the help of Courant-Friedrichs-Lewy stability condition. Using partitioning by spatial variables allows effective application of parallel processing technology OpenMP.

Testing of the proposed algorithm and program had been carried out. The testing showed good coincidence of analytical and experimental data with numerical modeling results. The main testing results are brought in [25].

5. Results

The formation of superdense clumps resulting from the collision of molecular clouds is an interesting mechanism that explains the appearance of new stars. These dense clumps are gravitationally unstable according to Jeans and are the precursors of new stars and star clusters. Thermal pressure in the MC is not enough to prevent gravitational collapse.
The calculation results showed that the mutual collision of the MC leads to the formation of a superdense region on the surface of the collision, in which ever denser gas clumps are constantly formed. Small irregular pulsating structures appear on the shells of both MCs due to instabilities of the Rayleigh-Taylor type. Strong shock waves appear at the boundary between the clouds, forming a thin dense disk of compressed gas (Fig. 2 is shown in red). Inside this disk, the pulsation structure in thin surface shells is enhanced due to the instability of the thin shell, while the thin shell is limited on both sides by continued compression and accelerated by the continuous movement of the clouds. The density of these clumps exceeds the initial density by several orders of magnitude, which leads to the formation of gravitationally unstable regions. In figures 2, 3, and 4, green indicates the dimensionless density 5, red color indicates 4000.

Figure 3. Formation of the vortex and ring-like structures at the developed stage of MC collision process

Vortices form ring structures on the surface of the cloud. Over time, they turn into vortex tracks and initiate vortex pins.

In order to find out the structural features of the vortex flow, the calculated fields of the Q-criterion [27] are presented. The second invariant of the velocity gradient tensor is used to identify areas of unevenly scaled vortex concentrations. Maps of the color palette of local speed, shown on the surfaces of the Q-test, illustrate the intermittency of the gas flow. In Fig. 3 and Fig. 4 figures of the Q-criterion (Q=1000) for moments of dimensionless time t = 225 and t = 250 are shown. Vortices have a lower distribution density inside the mixing region; on the boundaries and surfaces of elongated filamentous buds, the vortex distribution densities are much higher and show a local velocity slope in different MS regions.

In situations with insufficient smoothness of pressure/energy fields in areas with high gradients, the spatial intermittency of the outer layers of the clouds and their lenticular lumpy (core) deformation lead to coherent and wave perturbations inside and out. The process is accompanied by Kelvin-Helmholtz (KN) instability and a violation of the gas density above the perturbed surface layers of the clouds. Coherent increasing oscillations caused by extremely
strong contractions of the core of lenticular clouds become clearly observable temporary pulsations as one cloud penetrates another. Fig. 5. It is very likely that this process is generated through the exchange of energy in high-gradient outer layers and the deformation of a lumpy membrane wave. The nonlinear instability of thin shells (NTSI) in the gas phase can play a decisive role in starting this process.

Figure 4. Formation of the vortex and ring-like structures at the developed stage of MC collision process

Figure 5. The formation of coherent vibrations arising from the collision of molecular clouds

During the calculations, it was found that temporary pulsations appear during the penetration of one cloud into another. A structure is formed that leads to the interaction between the clouds and the interstellar medium by means of coherent pulsation (Fig.5). This process is generated
through the exchange of energy in highly gradient outer layers and deformation of the membrane structure. The nonlinear instability of thin shells in the gas phase can play a key role in starting this process. The Kelvin-Helmholtz instability leads to the deformation of MCs, the appearance and formation of protonuclei - gravitationally bound structures.

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