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Modeling of density stratification and filamentous structure formation in molecular clouds after shock wave collision

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ABSTRACT

The article submits the results of 3D computational modeling of the adiabatic interaction between a shock wave and molecular clouds. According to the problem set, two spherical clouds with pre-established density fields interact with the post-shock medium of supernova blast remnants. Gas flow evolution of molecular clouds is derived by solving the time dependent equations of mass, momentum, and energy conservation. High resolution numerical grids (more than two billion nodes) were used in parallel calculations on multiprocessor hybrid computers. The collision was found to give rise to the supersonic turbulence in a cloud mixing zone, the formation of filamentous structures, the significant stratification of gas density, the disruption of clouds, and the transformation of emerging structures. The peculiarities of cloud-clump-shell fragmentation of filamentous structures are discussed.

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1. Introduction

The last years have seen great advancement in understanding of the processes governing the formation and evolution of stars. Supersonic turbulence is likely to contribute significantly to star formation processes in filament swellings and clumps occurring inside giant molecular clouds (GMC) [1,2]. These formations are wide spread in the universe. Molecular clouds (MCs) may evolve to structure of interlacing and connecting filaments [3,4]. This web of spatial voids, made up of slightly or highly compressed gas fibers or enclosures, depends on the external influence on the interstellar medium (ISM), and has an indirect action on the condensation of cores formed into more massive intersected filament clumps that later could become protocores – embryos of future stars [5,6].

One of possible scenarios of filament structuring initiation is a collision of MCs with strong shock waves of another gas formations propagated in the space [7]. The shock wave (SW) interaction generated by proliferation of supernova explosion remnants and the molecular clouds leads to supersonic turbulence of gas in MCs, deep density stratification and their destruction followed by formation of filamentous structures. The shock wave impact accompanied by intense dynamic interaction of filaments with each other leads to the significant redistribution of gas density in clouds [8]. MCs/SW turbulization is initiated by instability on perturbed interface separating cloud gas and ISM of different densities and during for a time shock wave is passed through cloud region. Any perturbation initially present on the interface will be amplified following the refraction of the shock. The amplification of perturbations leads to vorticity generation resulting from the mismatching of the pressure gradient of the shock and the local density gradient across the interface. This phenomenon is known as the Richtmyer–Meshkov (RM) instability [9,10]. As the interface between the two fluids becomes more distorted, secondary instabilities, such as Rayleigh–Taylor (RT) and/or Kelvin–Helmholtz (KH) shearing instability, can also develop and a region of turbulence and mixing ultimately results. Spatial scale of initial perturbation is small and it is important to realize that the very fine computation mesh should be used in simulation. The present simulation has been performed to study vortex structuring in the molecular clouds formations disbalanced after collisions with a shock wave, and associated with turbulization and filaments formation during these processes. The authors gain insight into the effect of clouds' mass and form (spherical initially) on the dissipation of kinetic energy of a shock wave in a mixing zone of clouds and on the formation of filaments. The occurring filament formations governed by the vortex flow of a shock wave interact with each other and develop in the gradient regions of the gas density fields. It is shown that at specified points of time there occur ultra-dense regions, with the density contrast being an order of magnitude higher than the initial contrast in clouds. Evolution of such objects, running from the formation of filament rudiments to the moment, they

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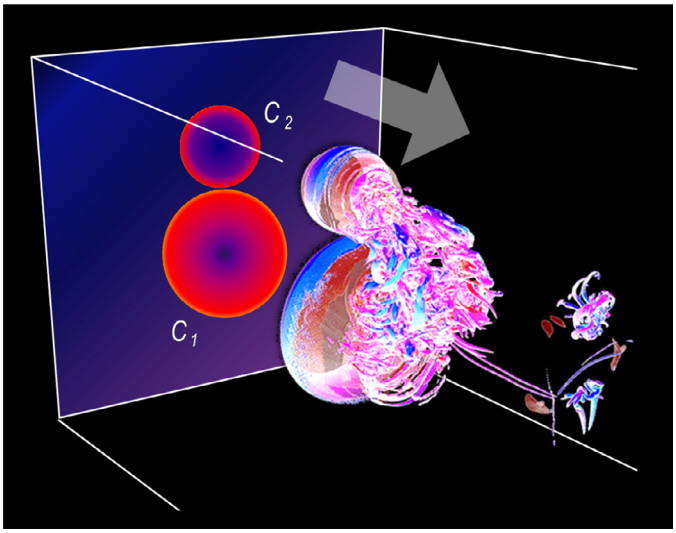

Fig. 1. Schematic representation of the task.

reach the stellar densities, covers a vast range of spatial and time scales.

The article analyses the density ablation and fragmentation of clouds matter, investigates the process of filament formation and gas density stratification (shell-clumpy structure) as a result of SW/MCs collision. One of the first numerical solutions identifying filament structures was recorded in [7]. The solution was received using grids of about 12,500 cells. Quality results for this primary computational progress were obtained in this report. Recent related publications can be found in [11–14].

Applying state-of-the-art high performance computing technologies we have realized a numerical simulation of complicated gas dynamics task using calculation grids with more than two billion nodes.

2. General formulation

We study the three-dimensional strong shock wave and molecular cloud interaction in a configuration where a plane strong shock frontal of supernova remnant gas runs onto systems of two clouds of spherical form.

The schema of SW/MCs collision is shown in Fig. 1. At the moment of collision a shock wave touches outer MCs boundaries. Special rule of density radial distribution is used to represent more realistically the density smoothing profile on the border between the clouds and the outer medium. Appropriate functions were taken according to recommendations given in [11–13].

The density radial distribution formulas for clouds C_1 and C_2 are the following:

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

$$\rho(r) = \rho_{ism}\Big(\chi + \frac{\alpha}{\alpha + 1}(1 - \chi)\Big), \tag{2}$$

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

Form factor α in (2) can be calculated by formula:

$$\alpha = exp\{min[20.0, 10 \cdot ((\frac{r}{R_{cl}})^2 - 1)]\}. \tag{3}$$

Several parameters in these formulas controlling the steepness of clouds border were changed to improve density smoothing. The key physical parameters and assumptions of the present task were correlated by data from [17,18]. The interstellar medium consists of relatively warm matter with $T_{ism} = 10^4$ K, the temperature of colder MC gas $T_{cl} = 10^2$ K. The ambient gas density of the outer cloud medium $\rho_{ism} = 2.15 \times 10^{-25}$ g/cm^3, the gas density in the undisturbed cloud centers $\rho_{cl} = 1.075 \times 10^{-22}$ g/cm^3.

Characteristic (conventionally diffused) radius of each cloud R_{cl} is equal to 0.1 pc. For system of two clouds (C_1, C_2), the mass of each is (approximately, considering fuzzy boundary) equal to $0.005M_\odot$ or $0.01M_\odot$ respectively, in solar mass fractions. The initial density contrast between the MCs centers and the interstellar medium is $\chi = 500$. Mach number M_{sw} of incident shock wave is equal to seven, post-shock plasma density $\rho_{sw} = 8.6 \times 10^{-25}$ g/cm^3, temperature $T_{sw} = 1.5 \times 10^5$ K, velocity of shock wave $U_{sw} = 104$ km/s. The thickness of post-shock wave front is 2–5 pc, which is much greater than the radius of a cloud. The period of time the shock wave propagates the upper cloud diameter - t_{swoc} is about 2000 years ("swoc" – shock wave over cloud). This value is used as a scale for non-dimensional time.

3. Numerical approach and realization

Gas movement generated by shock wave and molecular clouds collision is described with a set of Euler equations which are conservation laws for mass, momentum, and energy

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \mathbf{F} = 0, \tag{4}$$

$$\mathbf{U}=(\rho, \rho\mathbf{u}, e)^T, \quad \mathbf{F}=(\rho\mathbf{u}, \rho\mathbf{u}\mathbf{u} + p, (e + p)\mathbf{u}), \quad e=\frac{p}{\gamma - 1} + \frac{|\mathbf{u}|^2}{2} \tag{5}$$

where ρ is the mass density, $\mathbf{u} = (u, v, w)$ is the velocity vector. The total energy density e and gas pressure p are related through the ideal gas closure, where adiabatic index - $\gamma = c_p/c_v$ is equal to $\gamma = 5/3$.

Accuracy of numerical solution of multivariable problems in supersonic gas dynamics is eminently important in astrophysics phenomenon simulation. High-order accurate difference schemes have guaranteed monotonicity preservation of conservation laws. They are based on Godunov approach [19] to proof linear, first-order upwind schemes. The nonlinear, second-order accurate total variation diminishing (TVD) approach provides high resolution capturing of shocks and prevents unphysical oscillations, therefore it describes the local discontinuity preserving hyperbolic conservation laws [20,21]. The TVD maintains a nonlinear stability condition. The total variation of a discrete solution defined as a measure of the overall amount oscillation in velocity $\mathbf{u}$ is:

$$TV(u^t) = \sum_{j=1}^{N} |u^t_{j+1} - u^t_j| \tag{6}$$

The flux assignment scheme with condition $TV(u^{t+\Delta t}) \le TV(u^t)$ can guarantee that the amount of total oscillations will have a limit. Different TVD limiters are used: *minmod, superbee, vanleer*. The *vanleer* limiter proves to be preferential in our solution. TVD scheme is an approbated and robust method to solve systems of Euler equations. Such an approach and a sampling of physical coordinates [22,23] have enables us to take an appropriate parallelization and accelerate computing. Numerical experiment is performed using different spatial resolution of physical description of SW/MC_s collision in space. Grid sizes from $512 \times 256 \times 256$ to $2048 \times 1024 \times 1024$ units were used in systematic calculations. Spherical clouds radius corresponds to 128 grid nodes. The number of nodes in this zone exceeds the spatial resolution level, which is necessary to resolve correctly density and velocity turbulence fluctuations over energy high gradient gas layers. The level of zonal

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