Coherent instabilities leading to fragmentation of molecular clouds interacted with shock wave of supernova blast remnants

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Abstract

The purpose of the present numerical simulation is to analyze density fragmentation process in small molecular clouds shocked by a shock wave of supernova blast remnants. We consider dynamical formation of MC structures associated with Kelvin-Helmholtz and Richtmayer-Meshkov instabilities taking place in a zone of the cloud and interstellar medium interaction. Form driving effects for one and two cloud systems are studied. The MC gas flow evolution 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 first of modelling task was a single cloud SW/MC interaction. In the second case two initially spatially perceptible clouds with pre-established gravitational fields interact with the post-shock medium. The peculiarities of cloud-clump-shell fragmentation and formation of generated structures are discussed.

1. Introduction

Strong shock waves (SW) of propagated in the interstellar medium supernova remnants and interacted with molecular clouds (MC) are determined and can be explained by dynamical processes leading to switch of the trigger mechanism of gravitational collapse and star birth out of space heterogeneities. Numerical simulation of SW/MC interactions has more forty-year enhancement history of modeling and treatment of Kelvin-Helmholtz and Richtmyer-Meshkov instability factors and their influence on the shaping, fragmentation and MC destructions (Klein et al. 1994). Power and parallel calculation codes now can be used to study astrophysical processes taking into account models of magnetic fields influence and radiate cooling (Johansson & Ziegler 2011). The present study is a continuation of numerical hydrodynamic modeling similar to previous investigation for one and two cloud systems. To calculate fine details of cloud instability expansion we used grids with resolution up to $2048 \times 1024 \times 1024$ units. We have used author's 3D computer code, being controlled on hybrid computers using OpenMP and proved by tasks being to those under consideration.

2. Problem definition

We study three-dimensional strong shock wave and molecular cloud interaction (SW/MC) in a configuration which a plane strong shock frontal of supernova remnant gas runs onto single cloud or systems of two clouds of initial spherical form. The scheme of initial setup

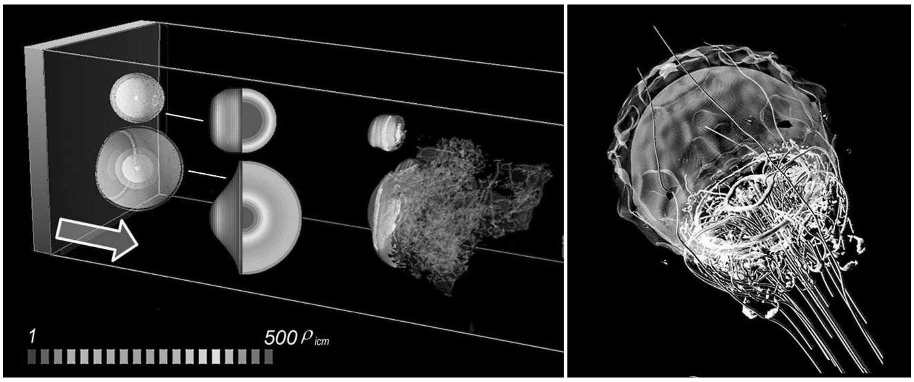

FIGURE 1. Initial setup for modeling of two cloud system interacted with post-shock SNR matter. Shaded contour plots of cloud density distribution at initial and particular instant are shown. On the right: density shell ($55 \cdot \rho_{icm}$ and Q-criterion field at t = 70 t_{sc} for a single cloud.

in the latter case is given in Figure 1. Gravitation influence is taken into account by means of prescribed cloud density distribution at the initial stage of the SW/MC interaction.

The assumptions of Klein et al. (1994), of physical parameters were determined. We suppose that interstellar medium consists of relatively heated matter ($\sim 10^4$ K) and cold heterogeneous dispersed molecular clouds ($\sim 10^2$ K) have higher density. We examine the hydrodynamic evolution of initially spherical and changeable in interaction process cloud or system of clouds in ICM. We specify the ambient temperature of the intercloud medium $T_{icm} = 10^4$ K, density $\rho_{icm} = 2.151 \cdot 10^{-25} g \cdot cm^{-3}$, temperature in the cloud at undisturbed state $T_{cl} = 100$ K, $\rho_{cl} = 1.0751 \cdot 10^{-22} g \cdot cm^{-3}$. We represent clouds as spheres of radius $R_{cl} = 0.05$ pc and 0.1 pc.

The initial setup consists of one or two cold and dense clouds embedded into a homogeneous, warm outer medium. At initial moment of time the shock wave touches cloud boundary. In case of two clouds they are exposed to shock simultaneously. In the case of SW interaction with a single cloud its density is taken as a constant. In the case of two clouds it is more realistic to represent the density smoothing profile on the border between the cloud and the outer medium. Appropriate functions were taken following to Pittard et al. (2009) and Johansson & Ziegler (2011).

Mach number M_{sw} of incident shock wave is equal to seven, post-shock gas density $\rho_{sw} = 8.61 \cdot 10^{-25} g \cdot cm^{-3}$, temperature $T_{sw} = 1.5 \cdot 10^5$ K, velocity of shock wave $U_{sw} = 104$ km/s. The thickness of post-shock wave front is $\sim 2 - 5$ pc, which is much greater than the radius of a cloud. Shock wave crossing time over alone cloud t_{sc} is equal to 960 years. Density contrast between the clouds and the intercloud medium $\chi = \rho_{cl}/\rho_{icm}$ is equal to 500. Initial cloud mass $M_{cl} = 0.0083 M_{\odot}$ in case of a single cloud modeling. For system of two clouds (C_1, C_2), the mass of each is approximately equal to $0.005 M_{\odot}$ or $0.007 M_{\odot}$. The computational areas used are parallelepipeds, $3.2 \times 1.6 \times 1.6$ pc in dimension for simulation of the system of two clouds. Spherical clouds diameter corresponds to 256 grid nodes. The lateral and outlet computational domain edges are determined as open boundary conditions for primitive variables.

3. Results and discussion

Details of SW/MC interaction were analyzed by using time tracing of reshaping forms during the clouds evolution. The influence of momentum instability in layers between

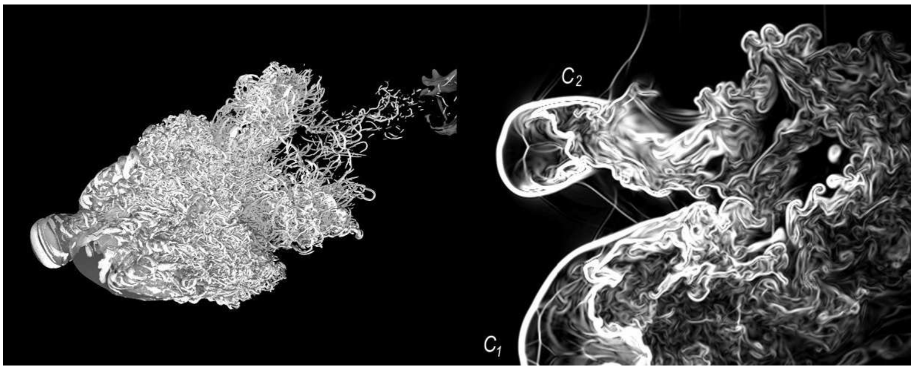

FIGURE 2. Vortex Q-criterion (Q = 100 s^{-1}) distribution and zoom-in of numerical schlieren for instantaneous density-gradient field at stage $t = 75t_{sc}$.

the cloud surface and the outer medium began to appear in amplification of density consolidations in fluctuated density fraction inclusions inside and outside (behind) the MC core.

Shock interactions of SW with abruptly accelerated superficial layers of clouds produce density perturbations. This process is accompanied by effect of the Kelvin-Helmholtz instability initiated by the momentum difference between cloud layers and outer medium. The after-effects of SW/MC interaction and cloud turbulent reshaping are illustrated by snapshots of a density shell and vortex zone formation for a single and two cloud structure shown in Figure 1 and Figure 2. Emerged instabilities are taken into account all in one, lead to generation of diversified vortex rolls, hairpins, clumps, pre-filament forms and fluid turbulent interfusion.

Shown on Figure 1 distribution of vortex indicator Q-criterion - second invariant of a velocity gradient tensor, reveals the existence of vortex ring-like and hairpin structures that are evidence of highly unstable nature of intermittent cloud density layers and deformed shells. Time evolution of MC turbulent fragmentation for a single cloud simulation is in acceptable correlation with the results of previously done modeling.

In model of gas flow over two clouds system the distribution of mass density for cloud C_2 has more uniformity contrary to distribution of density of cloud C_1, where the most part of mass concentrated in the core of cloud. This initial heterogeneous density field defines more rapid process of cloud shells stretching and particularly at stage of strong density compression very soon after SW passing. Sharp asymmetry of the velocity distribution in transitional zone between outer cloud boundaries leads to shock eddying near the selvage of folded shells. One can see how vortex trail outlet of cloud C_2 can generate changeable contrary swirled jets closely interacted behind of clouds (Figure 2, snapshot with Q-criterion distribution shown at the left). It looks like an aggregate of tangled vortex loops or hairpins. Some isolated plumes are periodically broken. The intensity of eddy formation is going up with increase of clouds mass involved into the movement.

Turbulence drives the fragmentation of dense cores and multiformity of spin profilamentary structures following the primary riffle shell and clump forms. The energy and density gradients on density shell edges are high correlated. It can indicate the filaments rudiments in such regions. Currents near edges involve the oblique collisions of secondary shock fronts that arise from the initial supersonic shock fluctuations, both over cloud recirculation zone and inside of it, as well as behind the shock wave (primary or

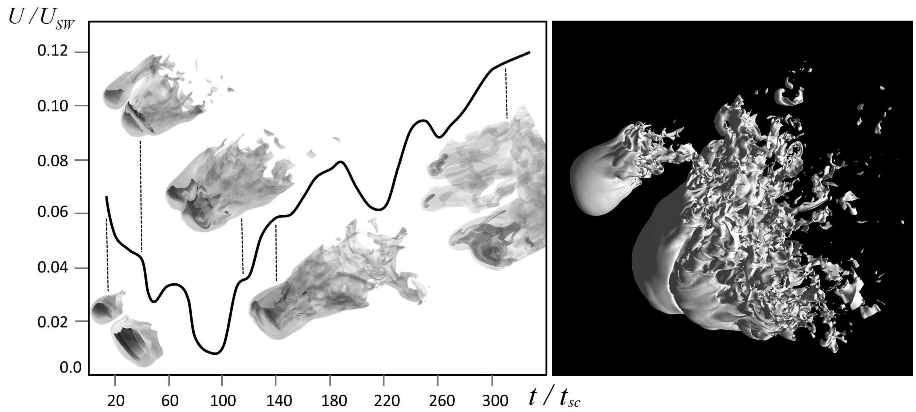

FIGURE 3. Drift rate fluctuations during the temporal evolution of two cloud structure.

secondary) intersection lines and discs. Supersonic turbulence occurrences initiated by strong shocks and instabilities in shear layers have been obtained using refined numerical grid in numerical solution. Over-dense confined formations, observed in calculations, are interpreted as a precursor of filament structures.

Process of density fragmentation is reflected on diagrams of mass density fraction alterations in time. Stages of unstable change of cloud forms and mass can be illustrated by the cloud drift velocity fluctuations (Figure 3). Cloud acceleration and deceleration is closely linked with area of density shell reformation, their augmentation or diminution as well as local high compression of substance that periodically split or merges clumps and filament rudiments. Supersonic disturbances increase the mass transfer and momentum linkage between superficial cloud layers and their surroundings, and as a consequence drift and crush of clouds can be accelerated.

Modeling results for a single and two cloud system evolution have been analyzed in supersonic gas dynamics manifestation. The work will be continued and current results can be used to elaborate the problem in question taking into account the expected rotation influence on cloud crushing and origination of filamentary structures for colliding astrophysics objects.

Acknowledgements.

The work has been funded by the Russian Foundation for Basic Research grants: No. 14-29-06055 and 14-07-00065.

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