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SHOCK-WAVE STRUCTURES AND INSTABILITY IN VARIOUS SCENARIOS OF MOLECULAR CLOUDS COLLISION

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Summary The aim of this work is the analysis of results for parallel numerical simulations of shock collisions between molecular clouds upon impact in different scenarios: with head-on, shifted and rotation interplay. These processes are accompanied by oscillating unstable perturbations in the distribution of matter density in new formed cloud residues. In clumps of remnants containing more condensed matter, the gas density can reach values that are at the initial level of pre-stellar formations, zones where new stars can form with a high probability. The generation of revealed coherent structures in new cloud formations unbalanced after a collision is determined by the hydrodynamic Kelvin-Helmholtz instability and, perhaps, by Nonlinear Thin Shell Instability effects, which trigger oscillation of density in the shock compression core and at the boundaries of nebular.

1 STATEMENT OF THE SIMULATION PROBLEM

Among different assumptions about star origination in the Universe the gravitational-turbulent model combines the assumptions about the reason for the creation of stars as a result of a collision of molecular clouds. We selected a hydrodynamics turbulent model for mutual cloud collisions, with an emphasis on taking into account only the kinetic energy aspect of molecular cloud collisions, in order to analyze only this effect, separating it from gravitational compression effects.

Different possible scenarios of a molecular cloud-cloud collision were realized in the numerical experiment – simulation of their mutual penetration in head-on and a glancing impact with taking into account the effects of possible nebulas rotation. The calculations were carried out as a continuation of the studies with the numerical approach, defining parameters and author code developed in [1]. The problems being solved consider collision and mutual penetration of supersonic compressible gas flows in the nonsteady definition using Eulerian equations for conservation laws of mass, momentum, and energy. Equations are solved on high refinement meshes with dimensions reached a level 2048x1024x1024 of nodes with adaptive Roe solver using the schemes of TVD type. Numerical realization was done using in-house software code developed for multiprocessor computers. OpenMP programming library for parallelization is employed. Calculation tuning with Intel VTune Amplifier XE is carried out for Xeon E2630 and Xeon E5 2650 Ivy Bridge processors. Authors HDVIS code is used for visualization and analysis.

Scheme of MCs collision and sample of numerical simulation of CCC realized in the study are shown in Fig, 1.

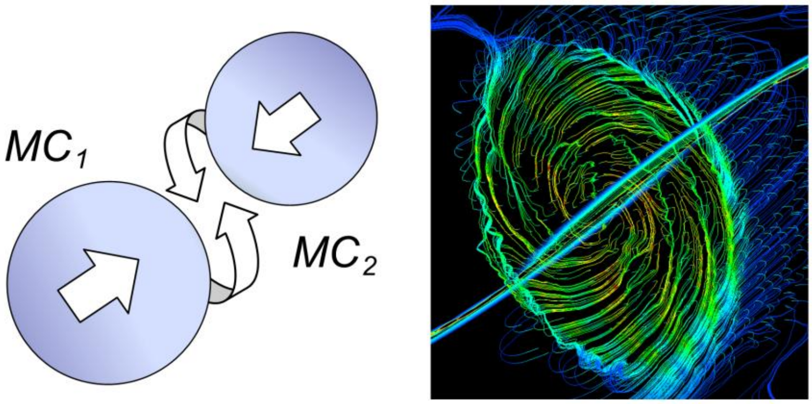

Figure 1: Morphing of MCs in mutual penetration process for head-on and glancing impact scenarios.

The numerical experiment was performed according to different impact scenarios between two clouds - MC_1 and MC_2. In them, oppositely directed clouds of different masses, sizes, and densities collide with each other at different oncoming velocity of 2.94, 4.71, 5.88, 11.77 km/s, which are varied in the calculation options. In the case of the glancing strike centers of MCs were displaced with different shift. Initial density contrast $\chi = \rho_{cl} / \rho_{ism}$ (density ratio between the MCs centers and in the interstellar medium ISM) was varied in the range: 25 - 500. Domain sizes used in the simulation were varied in 2 - 40 pc.

2 RESULTS AND DISCUSSION

The aim of simulation was study the influence of initial MCs impuls and oncoming velocities in collision process on sharp compression formed shock core and originated clumps distribution during process of fragmentation, density perturbation in them, and filaments ablation of clouds remnants. In some numerical realizations, the angular moment of rotation of the clouds around the collision axes was taken into account.

In numerical experiments it was found that during the time evolution of CCC morphing process goes through three stages: mutual clouds penetration with rapid growth of compression in contact layer; generation of lens-like supersonic core with time-depended transient stage; and origination of stochastic clumps-filaments set in bow shock compressed center. In a case with shifted impact details of gas flow perturbation are repeated with predictable spatial distortion of clouds remnants, redistribution and diminution of the integral influence of supersonic compression on this process.

At all stages of the development of the collision process, a distinct influence of gas stream instabilities on the nucleation and deformation of clouds clumps and filaments is observed. This is concerned with tangling of filaments and stretches gas flow with vortex turbulization inside clouds and on outer remnant surfaces with ablation of gas matter into outer ISM. This spatial evolution of post-collision remnants gas formation is illustrated in Fig. 1 and 2, where filaments and originated clumps in the glancing collision of contrary rotated nebulae are shown. Wave ripples are observed on the outer surface of the cloud in the form of local jets and fingers as consequences in the perturbation of the gas density field and oscillating clumps. Analysis of CCC consequences shows considerable spatial intermittency of dense layers of clouds and their lenticular curved deformation with matter concussion and oscillation. In the case, the off-center collision of clouds ripples and vortexes appear on the shell remnants cavity.

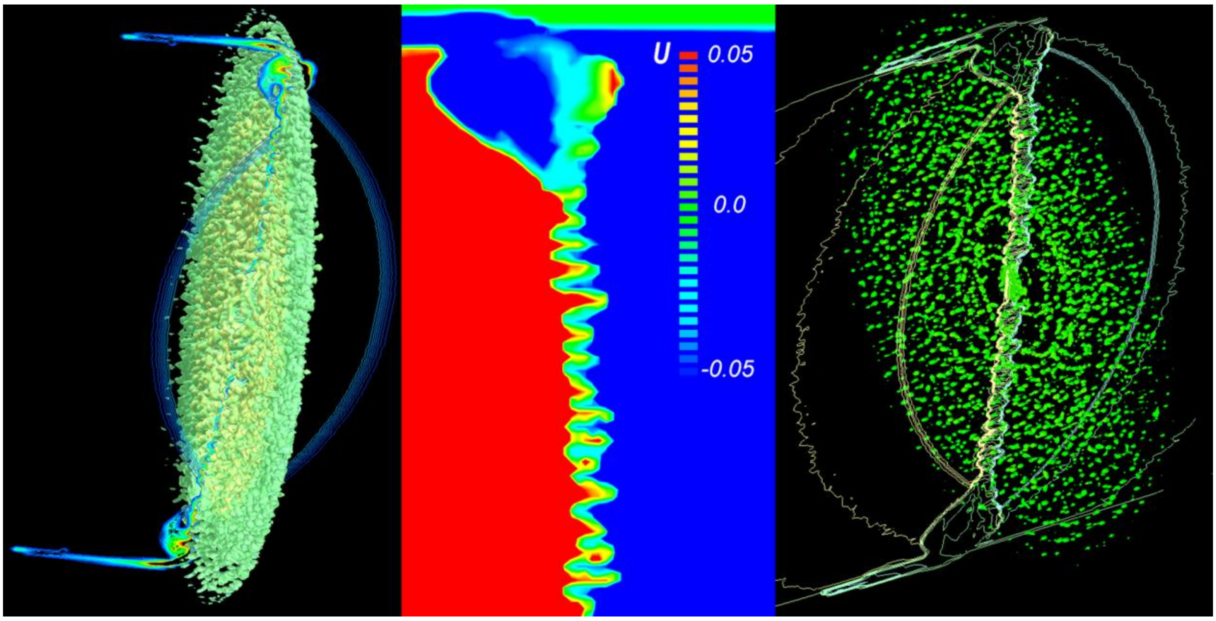

Figure 2: NTS Instability influence on to forming spatially intermittent shock compressed core: energy contours and isotachs in meridional cross-section plane of nebulae's formation; isodensity finger and filament structures over stagnation area and around clumps.

This process is provoking by Kelvin-Helmholtz instability and periodical fluctuations of gas sign-changing fluxes from ISM into outer layers of nebular with sharp density changing near overdense impact core during new clumps origination. Instability accelerates the generation of vortices inside the clouds formation, which is reflected in corrugated forms of shock core layers with over density inclusions and growing cavity in MC_2. During the central collision, the main gas tensions are accumulated over the stagnation surface of contrary gas streams. A compressed shock layer stochastically changes its density and structure of spatial blobs originated above stagnation points. The kinetic energy stress accumulated between jets on the contact spots is provoked by propagating of oblique shocks. Density and velocity fields in a shock-compressed core of colliding clouds are quite intermittent. Flow density and velocity perturbations initiated by extremely strong contractions of clouds' cores become clearly observable under the analysis of temporal pulsations of gas density fields in appropriate animations in visualization program used. Schematically, this dynamic process can be illustrated in Fig. 2, which presents an isodensity map and isotachs for one stage of flow oscillating in the collision zone originated by ram gas pressure on both sides of the stagnation zone. Flow jets have more high amplitude on flow braking boundary depending on collision kinetic energy amplification on the impacted stream front. This process is accompanied by the intensive kinetic energy interchange between clumpy inclusions and concomitant nonlinear deformations of them all over the direction of bow-shock layer moving.

Highly likely the decisive role in starting this process can be played by the NTSI (Nonlinear Instability of Thin Shell) - hydrodynamic instability, the mechanism of which is reasonably described in [2] and recently discussed in [3] of scenario of stars origination in unstable stellar wind collisions in a binary star system. A similar mechanism of perturbation was observed in our simulation and has been caused by misbalance of kinetic energy inside more compressed gas layers in thin lens shape core with respect to the ram pressure of contrary gas streams. Any imbalance in the directions of collision on either shock front direction can enhance perturbation of the shock interface and allow this instability to grow. In simulations performed the gas streams have contrary speeds and KHI can be excided or included equally possible. It can be assumed that NTSI tends to be prevailed in central areas of frontal shock over other instabilities.

After the passage of MC_1 through MC_2, with the rupture of the shell of latter, the gas density in the clumps that appeared outside the rupture area can reach the highest density values compared with the values observed throughout the entire evolutionary period of clouds' interplay. The effect of nebulae swirling manifested itself in an additional perturbation in the redistribution process of the generated compressed gas clumps. Density contrast in the clouds transformation zone can be thousand-fold higher than the initial average values. The numerical experiments considering different parametric cases of molecular clouds collision revealed that the density of originated clumps can reach large values and can be vary in the range of $10^{-21} - 10^{-19}$ g•cm^{-3}, which corresponds to the generally accepted values for the pre-stellar conglomeration.

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