Influence of the rotation of colliding molecular clouds on the structure of the forming protostellar area

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Abstract. The rotation of molecular clouds during their collision can play a triggering role in the formation of protostellar structures. The modeling carried out can make understanding the influence of angular momentum of rotation on lenticular core compression in clouds impact and originating clumps and filaments at all stages of nebulae colliding. The numerical simulation of a cloud-cloud head-on collision with and without rotation was performed with optimization of parallel acceleration of calculation on a multi-node and core cluster. Simulation of the GMC collision revealed the conditions for achieving high density in fragmented clumps corresponding to the pre-stellar local density consolidation in filaments and clumps at an attainable level of the onset of gas gravitational collapse.

1. Introduction
Star formation is a fundamental process of the Universe evolution. Over the past several decades, astrophysicists around the world have been trying to study these processes using experimental observations and to simulate this multi-scale extreme physics processes. A theoretical study continues to reveal the influence of turbo-gravity, radiation and MHD on external triggers of self-regulated over-compression in massive stellar clusters formatted in pre-stellar zones. Processes of formation such areas after the collision of giant molecular clouds (GMC), hypervelocity jets and gas remnants interplay as a consequence of supernova explosion are study intensively. The introduction in [1] and preface [2] gives a fairly complete description of recently modelling methods with a large number of cited publications. The formation of star clusters in pre-stellar areas requires the rapid packing of giant amounts of gas and other matter into a small space. How this formation occurs has yet to be clarified. In [3] authors proposed the collision of giant molecular clouds (GMCs) as a likely formation mechanism of young massive clusters.

Different approaches, among them the SPH simulations, taking into account the effects of gravity, turbulence and magnetic interplay of contrary moved condensed astro-objects are performed in pioneering work [4] and in last study [5] can be noted. The influence of emerging hydrodynamic instabilities on collisions, such as RT, KH Instability, Nonlinear Instability of Thin Shells (NTSI) in formation of superficial layers of counter streams and their consequences for reformating clouds structure have been noted in many works [6, 7].

Compressed layers in cores are susceptible to thin-shell instabilities, creating a ‘corrugated’ shock interface, which can trigger the distribution of isolated gas clumps in evolution. The compression processes, taking into account the rotation of nebulae and additional centrifugal
forces influence, can increase probably the condensation rate of pre-stellar formation. Against the general background of publications on topic of Cloud-Cloud Collision (CCC) description, the number of studies taking into account the angular momentum of clouds rotation is relatively small. Some suggestions about the role of rotation in the change in the kinematic structure of the spiral molecular clouds were analysed in [8]. This study revealed some details of rotation influence using modern astrophysical observation techniques. It was noted that the clouds rotate with some acceleration and was found that cloud is unstable against gravitational collapse. The study show that rotation can significantly extend the evolution time of the resulting residual structure compared to cases without rotation. The growth of angular velocity leads to clouds expansion, to perceptible redistribution of kinetic energy in the collision zone.

2. Modelling approach

We simulate MCs collisions with scenarios of head-on mutual penetration of clouds, with and without addition rotation of nebulae using CAF parallel code. Modelling is carried out an Eulerian description with an emphasis on taking into account, first of all, force action, in order to analyse, basically, this effect, separating it from the forces of self-gravity, which are excluded from consideration at this stage of research.

Flow impact is described by a set of Eulerian equations in conservation form:

$$\frac{\partial U}{\partial t} + \frac{\partial F_i}{\partial x_i} = 0,$$

where $U = (\rho, \rho u_i, E)^T$ – are conservative variables; $E = \rho \left( \frac{1}{2} u^i u_j + \frac{P}{(\gamma - 1) \rho} \right)$ is a full energy; $F(U)_i = (\rho u_i, \rho u_i u_j + P \delta_{ij} u^j, u_i E + P \delta_{ij} u^j)^T$ are fluxes; pressure $P$ is calculated by the equation of state using adiabatic index $\gamma = 5/3$.

Solving three-dimensional problems on grids with high resolution, $1024^3$ and more, requires a lot of computer time. Traditionally, MPI is used to build parallel algorithms designed to run on supercomputers [9]. This is an efficient but rather complex parallelization technology. Therefore, software developers do not use this technology as often. Successful work on MPI requires programmers to handle a large number of subtle implementation details, such as specifying point-to-point broadcasting operators, broadcasting, specifying an explicit communication schedule. MPI is usually criticized as low-level and is sometimes called a 'parallel programming assembler' [10]. Parallel programming models, such as Partitioned Global Address Space (PGA) with direct access to remote memory, can significantly reduce the costs of programmers to obtain parallelization efficiency similar to MPI [11].

Some features, such as collective inline procedures, commands, and error handling on image failures, have been deprecated in the Fortran 2008 standards. They have become standard in Fortran 2018 with the adoption of the Terms of Reference [12]. Coarray Fortran [13] is a good alternative to the MPI standard from - due to the usual Fortran syntax, the simplicity and consistency of arranging arrays on supercomputer nodes and sending messages. Most of this work is done by the compiler. Coarray parallelization can increase to a great extent the speed of astrophysics problems simulation especially if is used in a super-large number of computational nodes and linked vector of the primitive variables [14].

In the previous version of our program StarDust, the OpenMP and CUDA parallel programming technology was used to speed up calculations [15]. It allowed performing calculations on 40 cores of one server node were done in an acceptable time. The addition of the rotation influence of clouds in calculations with more than one billion nodes significantly increased the time of calculation. In numerical experiment we use a parallel version of Coarray Fortran (CAF) [16, 17]. The system of Euler equations (1) is solved using the Roe solver for the TVD scheme. In addition, splitting by physical coordinates is used. Let $Q$ denote the one-dimensional operator that takes the solution from the step $u(x,t)$ to the step $u(x, t + \Delta t)$. For
a three-dimensional problem, the transition can be represented as:

\[ u^{t+\Delta t} = Q_x Q_y Q_z u^t \]

To preserve the symmetry of calculations in 3D case, we will use the following operators.

\[ u^{t_1+2\Delta t_1} = Q_x Q_y Q_z Q_x Q_y Q_z Q_x Q_y Q_z u^{t_1} \]
\[ u^{t_2+2\Delta t_2} = Q_y Q_z Q_x Q_x Q_y Q_z Q_y Q_z Q_x u^{t_2} \]
\[ u^{t_3+2\Delta t_3} = Q_z Q_x Q_y Q_y Q_x Q_z Q_x Q_y Q_z u^{t_3} \]

To use parallelization using Coarray Fortran technology, the program needs to make small changes to the data structure. An array has been introduced that stores general information that is distributed across images. CAF syntax allows you to work with remote data that can be located both on one node and on different server nodes. The created array stores information that allows parallelization for each coordinate independently of each other. This array is designated in the code as ArrayCom. Information is stored in each image. The image from the sender image directly transfers data to the recipient’s image memory using CAF syntax. When assembling the program, the Fortran 2018 programming language and the Intel Parallel Studio XE 2019 compiler were used. Comparative calculations were carried out on one cluster node with two 12-core processors. We compared the acceleration obtained using the OpenMP and CAF technologies for systems with shared memory. The comparison showed almost equal acceleration in parallel operations with a small but quite tangible advantage of Coarray Fortran.

In this regard, a modification of the program was implemented using the CAF technology. The Fortran 2018 programming language and the Intel Parallel Studio XE 2019 compiler were used. Comparative calculations were performed on one cluster node with two 12-core processors. We compared the acceleration obtained using OpenMP and CAF technologies for systems with shared memory. The calculations showed almost the same acceleration in parallel operations with a small but quite tangible advantage of Coarray Fortran with accompanying operations and actions. Rough parallelization can greatly increase the speed of modeling astrophysics problems, especially if it is used in an extremely large number of computational nodes and associated vector of primitive variables. The simulation of the nebulae collision presented is a continuation of serial modelling gas-dynamical processes occurring in ISM [18].

![Figure 1. Scenarios of MCs collision.](image)

Author’s Java system of visualization is used for results analysis. The main, time-consuming rendering operations in the post-processor are maximally parallelized.
3. Simulation setup
We simulated head-on impact and mutual penetration of initially spherical forms MCs of dissimilar in size and matter distribution, with the different rotation schemes being varied. Scenarios of CCC implemented are shown in Fig. 1 and noted as: a) head-on collision without rotation; b) the impact of the non-rotated cloud with a rotating one; c) clouds colliding with rotation in the same direction; d) clouds mutual penetration with a counter rotation. The axes of the rotation of clouds coincided with the impact direction.

It was assumed that oppositely moving clouds collide with each other with relative colliding velocity of 5.32 km/s. The speed of sound in the ISM: \( c_s = 11.772 \text{ km/s} \) was taken as a unit of speed. The angular velocity of rotation was taken equal to \( \Omega = 2.5969 \cdot 10^{-15} \text{ s}^{-1} \).

Figure 2. Time evolution of CCC follow scenario (d) from stage \( t = 145 \) to \( t = 1195 \).

4. Modeling
Main stages of MCs colliding evolution can be distinguished as: monotonic compression of gas in the lenticular core of the impact zone, accretion of unstable deformation of blobs - inclusions inside the core, and a rapid increase in the number of clumps and filaments observed both in front and behind the compressed core. This is common to all considered collision scenarios.

In situation with initial rotation by solid body law the centrifugal forces lead to rapid enlargement of core in radial direction. Under the influence of rotation, vortex rings - filaments appear at the periphery of the clouds. They have an intermittently broken structure with repetition of the local angular acceleration of gas. Time and spatial reshaping of colliding clouds are illustrated in Fig. 2 – animation frames of CCC evolution, where originated clump
and filaments embryos is trigger in a situation then MCs are rotating in contrary direction by scenario (d).

In these frames of animation iso-surface with iso-density contrast $\chi = 2$, as the background image of interstellar medium ISM is shown. The far half of iso-surface is shown. Isodensity for $\chi = 10000$, changeable in time is given in the center of scene. On this surface, a map of the distribution of tangential velocity contours is shown. Wisps of originated clumps and filaments

![Figure 3. Streamlines and azimuthal pathlines in CCC for the case of counter-rotating collision (d).](image)

are fragmented and redistributed across the rings around the impact axis and on the periphery. Gas streams move from the zone of the central stagnation spot to the periphery with spatial repetition of compressibility. Change in the angular momentum of rotating of new formations leads to the emergence of peripheral filaments in the outer layers at the middle stage of collision.

Changes in the velocity fields lead to the formation of gas flow moved in spiral channels diverging from the impact spot and the separation of toroidal zones at the periphery with additional compression of gas blobs in the lenticular core. An increase in the number of isolated in core by density clumps accompanies an increase of oncoming finger-like local jets passing through the surface of deceleration of counter streams. Details of the compressed core formation and flow configuration near of stagnation zone are given in Fig.3.

One can see a network of spiral fluid particle trajectories and streamlines associated with dedicated clumps with iso-density surface $\chi = 75000$ at stage of evolution $t = 1195$. The tangential path trajectories from clumps starting inside the impact zone are shown on the right in the figure. On the left, the streamlines over the stagnation spot are shown. Flocks-like vortex inclusions (red-colour) are shown inside this zone. One can pay attention to spirally twisted streamlines around more compressed blobs with periodic excitation of them inside and on the periphery of new formation. This is accompanied by KH instability and stochastic growth of 'finger' structures azimuthally repeating. When the clouds swirl, gas flows in their final movement form a spiral network of channels through which the gas is redistributed near the stagnation surface of impact. There are many confluent streamlets tending to the curves of attraction, towards and away from the axis of rotation of the clouds. Observed in simulation gas flow structure repeat the structure inherent in multi-armed spiral galaxies, in which moving of star clusters within is repeated in tails-like spirals [8]. At all cases of CCC simulated by different scenario, a distinct influence of gas stream instabilities on the nucleation of originated clumps and filaments is observed. Local compression shocks on the stagnation interface can be propagating via less dense gas channels between inclusions inside the core with increasing density and temperature gradients. As ram pressure of collision zone increases, density perturbations begin to increase under influence of NTSI effects, noted in [6, 7]. This effect clearly observed in the simulation performed. Bending deformation spread throughout the compressed core radially and azimuthally accelerates the generation of vortices inside the clouds formation, which is
Figure 4. The possible distribution of pre-stellar critical over-density clumps of the case (a) and (d).

reflected in corrugated forms of shock layers. Comparison of the structure of such corrugated formations for the calculated cases showed that the effect of clouds rotation during the collision and mutual penetration significantly increases the thickness of the lenticular core formation of the interpenetration of counter streams through oscillated layered stagnation zone. The penetration depth of opposing jets here can be increased by one and a half to two times, which significantly increases the level of gas oscillations and exchange processes in the corrugated areas of impact. Any imbalance in the directions of shock pressure and either energy gradient can enhance perturbation of the stream interface and leads to growth fluctuation of velocity and energy field.

Figure 5. Fields of density contrast and local vortex for the case of collision (a) without rotation of clouds.

The prediction of the formation of possible pre-stellar nucleation zones was carried out on the basis of a search of spatially limited over-compressed clumps where the Jeans conditions for gas matter consolidation in small volumes are satisfied and there are carried out favorable
conditions for gas sinks formation, which can be a trigger of the self-gravity mechanism switch are satisfied, according to known SPH methods [21].

Two ‘sink-creation’ were used, among them maximally reached compressibility of clumps and negative velocity and acceleration divergence – that favorable to condensing flow in these bounded places. Calculation of velocity field divergence with negative value excretion and their comparison with density fields can be used to find areas where places of potential star-triggering are possible. In these areas, the most favorable conditions for local collapse of pre-stellar matter and the birth of stars are reached. Such fields with a negative value of div (U) are shown in Fig. 4, there appropriate fields are crossing of clump cluster (χ > 60000) at the stage t = 1195, are shown of final spatial divergence of the most compressed clumps (blue color-coded) calculated by scenario (d). The rotation effect manifests itself in the clear selection of clumps with the narrow tape annular distribution. For the case of a head-on collision without rotation, this distribution is more uniform over the entire area.

A more rarefied and spatially extended along the axis of motion distribution of density and negative divergence fields is shown in Fig. 5. This is a final stage of the collision of non-rotated clouds. A qualitative analysis shows that the conditions for combining fields are less favorable here. Spatial vortex streams at the moment of complete passage of clouds are shown. Separated clump formations (maximal density contrast χ is over 600000) with concentric clumps distribution illustrate possible pre-stellar zones after a collision of giant molecular clouds.

After mutual penetration of one cloud through another, with the rupture of outer shell, the gas density in clumps that appeared outside can reach the highest density values compared with the values observed throughout the entire period of molecular clouds interplay. Gas density contrast in transformation zone can be thousand-fold higher than the initial average values. The numerical experiments conducted for GMC collision revealed that the density of originated clumps can vary over $10^{-19} - 10^{-18} g \cdot cm^{-3}$, which corresponds to the commonly accepted values for the pre-stellar conglomeration.

5. Conclusions
The numerical simulation of nebular collisions with and without rotation was performed with optimization of parallel acceleration of calculation on a multi-node and core cluster. Complicated redistribution in a swirled ring-like area outside the central stagnation spot of oncoming gas flows is revealed. Taking into account the rotation of molecular clouds introduces additional dissipative effects in the fragmentation of MCs remnants. More twisted and extended corrugated NTSI structures were revealed in calculations by the scenario of CCC collision with a counter-rotation in head-on moving. Simulation of the GMC collision revealed the conditions for achieving density in fragmented clumps corresponding to the pre-stellar local density consolidation in filaments and clumps at an attainable level of the onset of gas gravitational collapse.

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