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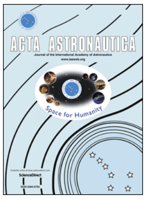

Model of turbulent destruction of molecular clouds

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ABSTRACT

We represent numerical simulation results of interaction process of supernova strong shock with interstellar molecular cloud in 3D. In the paper we neglect gravitation, heat conductivity and radiative losses. We analyze in detail processes of deformation and fragmentation of molecular cloud (MC). Formation of passed by and reflected shocks system, contraction and ablation of the matter is investigated in detail. The post-processor treatment and the results of calculations made it possible to find the following features of the molecular cloud matter – the vortexes formation, erosion and ablation.

1. Introduction

The space between the stars in the galaxy is filled by a rarefied substance which is called the interstellar medium (ISM). It consists of gas and dust and can be up to $10-15\%$ of galactic disk total mass [1]. Stars are formed from ISM and stars form ISM during their life and after their death. The structure of the ISM is nonuniform. In the ISM there are regions where the matter has large density. These nonuniformities appear due to the different reasons, but independently of their nature such clots or clouds (MC) are qualitatively different from the ISM. Fig. 1 shows molecular cloud IC 5146. The snapshot was done by Herschel telescope (ESA).

There are a number of papers devoted to the investigation of properties of molecular-dust clouds and their role in star formation process. In the pioneer papers [2,3] processes of fluxes interaction with different nonuniformities were investigated analytically. The influence of external flows on the properties of nonuniform regions were studied. With the growth of the computer power gravitation and magnetic fields were taken into account. In the papers [4–6] the problem of interaction matter flow and shock waves with a single MC was studied. These studies were done in 1D and 2D. Main hydrodynamical properties and magnetic fields behavior were studied.

In the papers [7–9,5,10] the problem was considered in 2D and 3D. In these and in a number of other studies it became possible to clarify complicated interactions which appear in the process of interaction of strong shocks with molecular-dust clouds. Development of the Rayleigh Taylor instability, ablation of the matter during turbulent flow formation, radiative cooling of the cloud's matter was studied.

In the paper [8] single-phase model of gas was used which allows to represent physical picture of the flow quite correctly. In the calculations it was supposed that nonperturbed ISM consists of relatively warm matter ($T\sim10^4$ K) and relatively small nonuniformly distributed cold ($T\sim10^2$ K) dense clouds [4,7,11]. Initially the clouds are in dynamical equilibrium with background gas [8].

In our paper we consider the process of interaction of high amplitude shock wave with the molecular cloud. The

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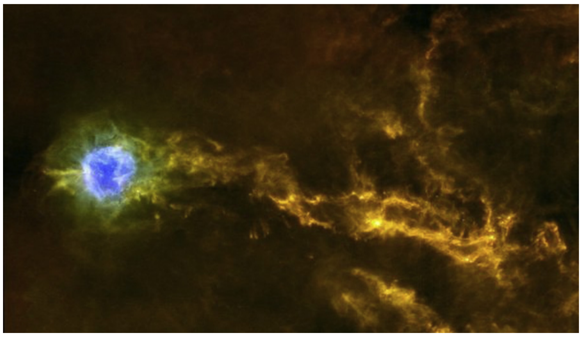

Fig. 1. Molecular cloud IC 5146. ESA picture/Herschel/SPIRE/PACS/D. Arzoumanian. http://kosmos.of.by/news/20326-teleskop-gershel-rassmotrel-samye-pervye-stadii-obrazovaniya-zvezd.html.

appearance of hypersonic gasdynamical flow, contraction, fragmentation processes and formation of turbulent flow in the cloud and surrounding media was simulated.

3D simulations of dynamical processes on refined grids require large computer power. For the simulations the parallel algorithm for nonstationary gasdynamical problems simulations was developed [10]. It was thoroughly tested on the problem of interaction of shock wave with the region of lower density [12]. For the acceleration of computations we have used OpenMP technology. The parallel computer code was developed based on high resolution difference schemes. The code is designed for the simulations of 3D gasdynamical problems described by Euler equations. For improvement of the quality of the parallel code we have used Intel V Tune Amplifier XE.

2. Formulation of the problem

ISM consists of relatively warm matter $\sim 10^4$ K. In the ISM there is a molecular cloud with much larger density than ISM density. The temperature in the molecular cloud is lower than the temperature in the ISM $T_{cloud} \sim 10^2$ K . The shock wave formed after supernova explosion (see e.g. [13]) hits the cloud situated in the ISM. Fig. 2 schematically represents plain shock wave (in the center) moving to the molecular cloud from the right side. We have used one-phased gas model. Initially the cloud is in dynamical equilibrium with surrounding gas. We neglect heat conductivity and radiational losses at the stage of interaction of the shock with the cloud. We use equation of state of the ideal gas with the adiabatic index $\gamma = 5/3$.

The density of the ISM is $\rho_a = 2.15{*}10^{-25}$ g/sm^3, the temperature $T_a = 10^4$ K, $u_a = 0.0$. The cloud density is $\rho_c = 1.075{*}10^{-22}$ g/sm^3, the temperature $T_c = 100$ K, u_c=0.0. The shock wave parameters are defined by the Rankine–Hugoniot conditions.

In our simulations we took shock wave Mach number M=7, density $\rho_{sh} = 8.6{*}10^{-22}$ g/sm^3, temperature $sh = 1.5{*}10^5$ K, velocity $u_{sh} = 1.04{*}10^7$ sm/s [4,7,11]. The parameters after the shock front do not change significantly during 2–5 parsecs which is much larger than the cloud radius. The cloud radius is r_c=0.05 parsec. The shock passes through the cloud diameter during ~ 960 years. At the initial time moment the shock contacts the left boundary of the cloud and at t=0 starts to interact with the cloud.

3. Governing equations and solution method

For the numerical simulations of the problem the parallel algorithm was created, it is based on difference schemes of TVD type [14]. The difference scheme is of second order of accuracy in space and time and allows to resolve shock waves and contact discontinuities with high spatial resolution and prevent appearance of nonphysical oscillations. For the verification of the quality of the code a number of 2D and 3D tests were done [10,12]. The testing showed good coincidence of computational results with the analytic solutions and experimental data. The fronts of the shocks were smoothed on 3–4 cells, contact discontinuities were smoothed on 3–5 cells.

Calculated area is presented by parallelepiped of size equal to $1024 \times 512 \times 512$ of cells along axes X, Y and Z respectively. In calculations the cells $\triangle x, \triangle y, \triangle z$ are set of equal sizes: $\triangle x = \triangle y = \triangle z$.

For reasonable spatial resolution of the processes which take place in MC it is necessary that the cloud radius should have at least 64 cells. The dimensions of our computational grid were taken $1024 \times 512 \times 512$. The smaller number of computational cells would lead to reduction of spatial resolution of the simulations.

3.1. *Initial and boundary conditions*

The calculated area is presented by parallelepiped with sizes $1024 \times 512 \times 512$. Bubble radius is 64 cells and its center is in the point with the coordinates c_x, c_y, c_z. At the left and right boundaries of the calculated area free boundary conditions are being set. At the rest boundaries, periodical boundary conditions are implemented.

3.2. *Dimensionless equations*

Let us write the system of three-dimensional Euler equations to dimensionless view. For this purpose let us represent each function as $f = f_0 f'$. Here f' – dimensionless value, f_0 – some constant dimensional scale factor. Typical values, which take part in the problem, are used as such scale factors. All values are brought to dimensionless ones in the following way:

$$t = t_0 t', \quad x = x_0 x', \quad u = u_0 u', \quad v = u_0 v', \quad w = u_0 v',$$
$$p = p_0 p', \quad \rho = \rho_0 \rho', \quad e = e_0 e'.$$

After carrying out calculations with the help of the introduced scale factors, it is possible to bring the calculated values to the dimensional view.

We will write the quantities values in the environment with index a, in the cloud – with c, behind the front of shock wave – with sh. At the initial time moment the area is filled by the gas with initial dimensionless density $\rho'_a = 1.0$, pressure $p'_a = 1.0$, sound velocity $c'_a = \sqrt{\gamma(\rho'_a/p'_a)}$. In the cloud with the radius r_c the gas has the following parameters: density $\rho'_c = 500$, pressure p_c=5. The shock wave, which moves from the left to the right, contacts the