The Collision of Giant Molecular Cloud with Galaxy: Hydrodynamics, Star Formation, Chemistry

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Abstract This paper will present the new results of mathematical modeling of the collision of giant molecular cloud and galaxy. The numerical model includes self-gravity hydrodynamics equation for gas component of galaxy and collisionless Boltzmann equation for stellar component. Numerical model includes important sub-grid physics: star formation, supernova feedback, stellar wind, cooling and heating function, and nonequilibrium chemistry to ion helium hydride. The numerical simulation of destroy of galaxy in high-density ICM will be demonstrated.

Keywords Computational astrophysics · Galaxy simulation · Numerical methods

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1 Introduction

The subject of modern astrophysics is the study of physical processes in the universe, their influence on the self-organization, and evolution of astronomical objects, as well as on their further dynamics and interaction. The description of astronomical objects is based on hydrodynamic processes. It is hydrodynamics that determines character of astrophysical flows, which leads to the evolution of astrophysical objects. Mathematical modeling is the main and often the only way for theoretical investigation of astrophysical flows due to the impossibility of carrying out total experiments. The numerical model of interacting galaxies is based on gravitational gas dynamics equations to describe the gas component and equations for the first moment of the collisionless Boltzmann equation with full tensor of velocities dispersion to describe the star component [1].

2 Hydrodynamical Model of Galaxies

To describe the gas components, we will use the system of single-speed component gravitational hydrodynamics equations, which is written in Euler coordinates:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = \mathcal{S} - \mathcal{D}, \qquad \frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i \mathbf{u}) = -s_i + \mathcal{S}\frac{\rho_i}{\rho} - \mathcal{D}\frac{\rho_i}{\rho},$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p - \rho \nabla(\Phi) + \mathbf{v}\mathcal{S} - \mathbf{u}\mathcal{D},$$

$$\frac{\partial \rho S}{\partial t} + \nabla \cdot (\rho S \mathbf{u}) = (\gamma - 1)\, \rho^{1-\gamma} \left(\Lambda - \Gamma\right),$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E \mathbf{u}) = -\nabla \cdot (p\mathbf{v}) - (\rho \nabla(\Phi), \mathbf{u}) - \Lambda + \Gamma + \rho^{\gamma}\frac{\mathcal{S}}{\rho} - \rho^{\gamma}\frac{\mathcal{D}}{\rho},$$

$$\rho E = \frac{1}{2}\rho \mathbf{u}^2 + \rho\varepsilon, \qquad p = (\gamma - 1)\rho\varepsilon = S\rho^{\gamma}.$$

To describe the collisionless components, we will use the system of equations for the first moments of the Boltzmann collisionless equation, which is also written in Eulerian coordinates:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) = \mathcal{D} - \mathcal{S}, \qquad \frac{\partial n\mathbf{v}}{\partial t} + \nabla \cdot (n\mathbf{v}\mathbf{v}) = -\nabla \Pi - n\nabla(\Phi) + \mathbf{u}\mathcal{D} - \mathbf{v}\mathcal{S},$$

$$\frac{\partial n W_{ij}}{\partial t} + \nabla \cdot (n W_{ij}\mathbf{v}) = -\nabla \cdot (v_i \Pi_j + v_j \Pi_i) - (n\nabla(\Phi), \mathbf{v}) + \rho^{\gamma}\frac{\mathcal{D}}{\rho} - \rho^{\gamma}\frac{\mathcal{S}}{\rho},$$

$$W_{ij} = v_i \times v_j + \Pi_{ij}.$$

The Poisson equation can be written as

$$\Delta\Phi = 4\pi G(\rho + n),$$

where p—gas pressure, ρ_i—density of ith species, s_i—speed of formation of ith species, ρ—density of gas mixture, n—density collisionless component, **u**—speed gas component, **v**—speed collisionless component, ρE—density of total mechanical gas energy, ρW_{ij}—density of total mechanical collisionless components energy, Φ—gravitational potential, ε—density of internal energy of gas, S—entropy, γ—adiabatic index, Π_{ij}—a tensor of dispersion of speeds collisionless components, $\mathcal{S}$—the speed of formation of supernova stars, $\mathcal{D}$—star formation speed, Λ—function of Compton cooling, and Γ—function of heating from explosion of supernova stars. The details of initial profile can be found in [2].

3 Sub-grid Physics

3.1 Star Formation and Supernova Feedback

The supernovae feedback we should use for SNII, SnIa, and other stars by stellar wind $\mathcal{S} = \mathcal{S}_{SNII} + \mathcal{S}_{SNIa} + \mathcal{S}_*$. To describe supernova feedback, we should use the initial mass function [3]

$$\phi(M_*) = \begin{cases} AM_*^{-1.3}, \ M_* \le 0.5M_\odot \\ AM_*^{-2.3}, \ M_* > 0.5M_\odot \end{cases}$$

stellar lifetimes function [4]

$$\tau\,(M_*) = \begin{cases} 1.2M_*^{-1.85} + 0.003Gyr, \ M_* \ge 7.45M_\odot \\ 10^{f(M_*)}, \ M_* < 7.45M_\odot \end{cases}$$

where

$$f\,(M_*) = \frac{0.334 - \sqrt{1.79 - 0.2232 \times (7.764 - log\,(M_*))}}{0.1116}$$

and nucleosynthesis [5]. For each type of stars, their share is determined $\mathcal{R}_{II,Ia,*}$ (see details in work [1]) and the rate of star formation is determined by the simple formula:

$$\mathcal{S} = \rho \times (\mathcal{R}_{SNII} + \mathcal{R}_{SNIa} + \mathcal{R}_*)$$

We note that the supernova explosion also contributes to the heating of the gas

$$\Gamma = 10^{51} \times (\mathcal{R}_{SNII} + \mathcal{R}_{SNIa}) \times M_{\odot} \times V^{-1}$$

The rate of star formation is taken from work [6].

3.2 Cooling and Heating Functions

The contribution to the cooling and heating functions is made by chemistry, which was described in the previous subsection, as well as supernovae feedback, in the following we will consider other sources of cooling/heating.

We will consider cooling functions in two temperature modes:

1. The low-temperature cooling. At low temperatures, the ionization of the elements H, O, C, N, Si, and Fe occurs due to collision. The collision frequency and the corresponding cooling function can be found in the work [7].
2. The high-temperature cooling. At high temperatures, the emission process for the elements H, He, C, N, O, Ne, Mg, Si, and Fe occurs. The cooling function can be found in paper [8].

To describe the heating function, we will consider the following two processes:

1. Cosmic ray heating. The process of ionization of hydrogen and helium atoms. The heating function can be found in operation [9].
2. Photoelectric heating from small dust grains [10].

3.3 Supermassive Black Holes

In recent years, many important results have been obtained in studying the physics of supernovae, the remnants of their explosion, and their feedback to more massive structures. So it was justified that dwarf galaxies cannot be the birthplace of supermassive black holes, which in turn is associated with the restriction of the mass of stars in such galaxies. In this regard, given that our main interest in the future is dwarf galaxies, we will not introduce a model of supermassive black holes in the mathematical model in the near future and dwell on their inclusion in a collisionless model [11].

4 The Chemistry

The collision of a giant gas cloud like the Smith cloud [12] with a Milky Way type galaxy is considered. The collision is considered in the model of the motion of a dense gas cloud through a rarefied medium. The characteristics of the gas components of the galaxy are as follows: $n_A = 10^{-1}\,\text{cm}^{-3}$—density of interstellar gas, $T_A = 10^4\,\text{K}$—interstellar gas temperature, $n_H : n_{He} = 9 : 1$—chemical composition of the gas component. Cloud Characteristics: $n_C = 1\,\text{cm}^{-3}$—density of cloud, $T_C = 10\,\text{K}$—cloud temperature, $v = 3 \times 10^5$ m/sec—cloud speed, and $n_C = n_H$—chemical composition of the cloud. The chemical composition of the gas mixture of interstellar gas and clouds are as follows: H, He, e, H^+, He^+, HeH^+, H_2^+. The physics model:

- Multicomponent one-speed gravitational hydrodynamics [13].
- The process of star formation [14].
- Effect of supernova explosions and stellar wind [3–5].
- Cooling functions at low temperature [7].
- Cooling functions at high temperature [8].
- Heating by cosmic rays [9].
- Photoelectric heating [10].
- Chemical kinetics to helium hydride ion [15].

The chemical reaction network:

1. Ionization of hydrogen by cosmic rays $H + c.r. \to H^+ + e$ [16].
2. Collisional ionization of hydrogen $H + e \to H^+ + 2e$ [17].
3. Collision ionization of helium $H + e \to He^+ + 2e$ [18].
4. Dissociative recombination of atomic hydrogen $H^+ + e \to H + \gamma$ [19].
5. Dissociative recombination of molecular hydrogen $H_2^+ + e \to 2H + \gamma$ [20].
6. Radiative association of the helium ion and hydrogen $He^+ + H \to HeH^+ + h\nu$ [21].
7. Dissociative recombination of the helium hydride ion $HeH^+ + e \to He + H$ [22].
8. Collisional recombination of the helium hydride ion $HeH^+ + H \to He + H_2^+$ [23].

Adiabatic index [24] (Table 1):

$$\gamma = \frac{5n_H + 5n_{He} + 5n_e + 5n_{H^+} + 5n_{He^+} + 7n_{HeH^+}7n_{H_2^+}}{3n_H + 3n_{He} + 3n_e + 3n_{H^+} + 3n_{He^+} + 5n_{HeH^+}5n_{H_2^+}}$$

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Table 1 The rate of chemical reactions

No	Speed reaction cm^3/sec	Activation (K)
1	10^{-17}	–
2	$e^{-32.7+13.5\times\ln T-5.7\times\ln^2 T}$	–
3	$e^{-44.1+23.9\times\ln T-10.8\times\ln^2 T}$	900
4	$3.92\times10^{-13}\times T^{-0.6353}$	–
	$e^{-28.6-0.7\times\ln T-0.02\times\ln^2 T}$	5500
5	10^{-8}	–
	$1.32\times10^{-6}\times T^{-0.76}$	617
6	1.4×10^{-16}	5000
7	$3.0\times10^{-10}\times(T/10^4\text{K})^{-0.47}$	1000
8	$1.2\times10^{-9}\times(T/10^4\text{K})^{-0.11}$	200

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