The numerical modeling of moving of dwarf galaxy through the intracluster medium

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Abstract. In this paper, we present the new results of mathematical modeling of dwarf galaxy movement through the intracluster medium (ICM). Our numerical model includes self-gravity hydrodynamics equation for the gas component of the galaxy and collisionless Boltzmann equation for the stellar component. We also included important sub-grid physics: star-formation, supernova feedback, stellar wind, cooling, and heating function, and non-equilibrium chemistry to ion helium hydride. As a result of our simulation, we provide density, pressure, and temperature for destruction processes in the high-density intracluster medium.

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 the 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 the full tensor of velocities dispersion to describe the star component [1].

2. The Physics Model

The numerical model of galaxies contains gas and stars components. To describe the gas components, we will use the system of single-speed component gravitational hydrodynamics equations. To describe the collisionless components, we will use the system of equations for the first moments of the Boltzmann collisionless equation. The details of initial profile construction for galaxies can be found in [2].

We use the supernovae feedback for supernovae core-collapse, supernovae Ia, and stellar wind of other medium mass stars. To describe the supernova feedback we are using the initial mass function from [3], stellar lifetimes function [4] and nucleosynthesis [5].
We will consider cooling functions in two temperature modes:

(i) 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 [6].

(ii) 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 [7].

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

(i) Cosmic ray heating. The process of ionization of hydrogen and helium atoms. The heating function can be found in operation [8].

(ii) Photoelectric heating from small dust grains [9].

There are many important results have been obtained in the study of the physics of supernovae, the remnants of their explosion, and their feedback on more massive structures in recent years. One of these results is that dwarf galaxies couldn’t be the place of birth of supermassive black holes [10]. This is why we don’t use a special model for supermassive black holes.

3. The Chemistry

The chemical composition of the gas mixture of interstellar gas and clouds: H, He, e, H\(^+\), He\(^+\), HeH\(^+\), H\(_2\)\(^+\). The chemical reaction network to helium hydride ion [11] with the reaction rate \(k\) (in cm\(^3\)/s) and the temperature \(T\) (in Kelvins):

(i) Ionization of hydrogen by cosmic rays \(H + c.r. \rightarrow H^+ + e\) [12],

\[
k_1 = 10^{-17}, T_1 = 0.
\]

(ii) Collisional ionization of hydrogen \(H + e \rightarrow H^+ + 2e\) [13],

\[
k_2 = \exp\left(-32.7 + 13.5 \times \ln T - 5.7 \times \ln^2 T + 1.5 \times \ln^3 T - 0.3 \times \ln^4 T + 3.5 \times 10^{-2} \times \ln^5 T - 2.6 \times 10^{-3} \times \ln^6 T + 1.1 \times 10^{-4} \times \ln^7 T - 2.1 \times 10^{-6} \times \ln^8 T\right), T_2 = 900.
\]

(iii) Collision ionization of helium \(H + e \rightarrow He^+ + 2e\) [14],

\[
k_3 = \exp\left(-32.7 + 13.5 \times \ln T - 5.7 \times \ln^2 T + 1.5 \times \ln^3 T - 0.3 \times \ln^4 T + 3.5 \times 10^{-2} \times \ln^5 T - 2.6 \times 10^{-3} \times \ln^6 T + 1.1 \times 10^{-4} \times \ln^7 T - 2.1 \times 10^{-6} \times \ln^8 T\right), T_3 = 900.
\]

(iv) Dissociative recombination of atomic hydrogen \(H^+ + e \rightarrow H + \gamma\) [15],

\[
k_{4,low} = 3.92 \times 10^{-13} \times T^{-0.6353}, T_{4,low} = 0,
\]

\[
k_{4,high} = \exp\left(-28.6 - 0.7 \times \ln T - 0.02 \times \ln^2 T + 2.4 \times 10^{-3} \times \ln^3 T - 3.1 \times 10^{-4} \times \ln^4 T + 1.4 \times 10^{-5} \times \ln^5 T + 5.0 \times 10^{-6} \times \ln^6 T + 5.8 \times 10^{-7} \times \ln^7 T - 1.8 \times 10^{-8} \times \ln^8 T\right), T_{4,high} = 5500.
\]
(v) Dissociative recombination of molecular hydrogen $H_2^+ + e \rightarrow 2H + \gamma$ [16],
$$k_{5,\text{low}} = 10^{-8}, T_{5,\text{low}} = 0,$$
$$k_{5,\text{high}} = 1.32 \times 10^{-6} \times T^{-0.76}, T_{5,\text{high}} = 617.$$ 

(vi) Radiative association of the helium ion and hydrogen $He^+ + H \rightarrow HeH^+ + h\nu$ [17],
$$k_6 = 1.4 \times 10^{-16}, T_6 = 5000.$$ 

(vii) Dissociative recombination of the helium hydride ion $HeH^+ + e \rightarrow He + H$ [18],
$$k_7 = 3.0 \times 10^{-10} \times (T/10^4 K)^{-0.47}, T_7 = 1000.$$ 

(viii) Collisional recombination of the helium hydride ion $HeH^+ + H \rightarrow He + H_2^+$ [19],
$$k_8 = 1.2 \times 10^{-9} \times (T/10^4 K)^{-0.11}, T_8 = 200.$$ 

Adiabatic index [20]:
$$\gamma = \frac{5n_H + 5n_{He} + 5n_e + 5n_{H^+} + 5n_{He^+} + 7n_{HeH^+} + 7n_{H_2^+}}{3n_H + 3n_{He} + 3n_e + 3n_{H^+} + 3n_{He^+} + 5n_{HeH^+} + 5n_{H_2^+}}$$

4. Numerical simulation of moving of dwarf galaxy through the intracluster medium

The moving of dwarf galaxy through the intracluster medium 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 $n_A = 10^{-1} \text{ cm}^{-3}$ is density of interstellar gas, $T_A = 10^4 \text{ K}$ is interstellar gas temperature, $n_H : n_{He} = 9 : 1$ is chemical composition of the gas component. Cloud Characteristics: $n_C = 1 \text{ cm}^{-3}$ is density of cloud, $T_C = 10K$ is cloud temperature, $v = 3 \times 10^5 \text{ m/sec}$ is cloud speed, $n_C = n_H$ is chemical composition of the cloud. The results of computational experiments of dwarf galaxy movement through the intracluster medium are presented in Fig. 1. The figure shows, that in front of the cloud a shock wave is formed, resulting from the interaction of cloud with ICM. At the edges of the galaxy, a shell is formed, the development of instability in which leads to the formation of Jellyfish-like galaxies. In areas of sufficiently high temperature, the conditions are created for the reactions that lead to the formation of the helium hydride ion.

5. Conclusion

We achieved new results of mathematical modeling of the dwarf galaxy movement through the intracluster medium. Our numerical model includes self-gravity hydrodynamics equation for the gas component of the galaxy and collisionless Boltzmann equation for the stellar component. We also included important sub-grid physics: star-formation, supernova feedback, stellar wind, cooling, and heating function, and non-equilibrium chemistry to ion helium hydride. The numerical simulation of ion helium hydride formation through destruction of the galaxy in high-density ICM is described.

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Figure 1. The density in $\text{cm}^{-3}$ (top left), the relative pressure (top right), the temperature in $T_A$ (bottom left) and density in $10^{-6} \text{ cm}^{-3}$ of the helium hydride ion (bottom right).

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