Major merging of galaxies in multicomponent numerical models: mass loss and exchange

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Abstract. The process of collision of two multicomponent galaxies is considered in detail based on numerical simulations of the dynamics of gravitating gas, stars and dark mass. To solve the equations of motion of the gas component, we use the Smoothed Particle Hydrodynamics method. Modeling of collisionless components is based on the N-body model. The computations of gravitational forces are carried out using both the approximate hierarchical TreeCode algorithm and the direct method of summing the gravitational contribution from all particles, which provides an accurate solution. This approach allows testing various models and evaluating the resulting errors associated with the calculation of gravitational forces and a finite number of particles in each of the components. Both methods for calculating gravity are software implemented as parallel codes for Nvidia Tesla GPUs. The estimates of the lost mass and the efficiency of matter exchange between galaxies are discussed depending on the model parameters.

1. Introduction

Various interactions between galaxies are a very important factor in their evolution. Astronomical observations demonstrate a wide range of such manifestations from weak tidal structures to major merging events with the formation of a single galactic system [1, 2, 3, 4, 5, 6].

The accretion of intergalactic gas and powerful shock waves in clusters of galaxies determine physical processes on a large scale, which manifest themselves in the mergers of substructures, the generation of cosmic rays and X-rays. Galaxies are not closed systems due to the loss and influx of matter in the form of supernova explosions, active galactic nucleus, jets, intergalactic accretion, major and minor mergers, stellar and gas flows, which is confirmed by a variety of astronomical observations and galactic/cosmological simulations [6, 7, 8]. Galactic merging events contain a very rich physics related to shock waves, star formation, complex heating and cooling patterns, chemical transformations, supernova explosions, providing feedback [2, 3, 9, 10].

The purpose of our study is to determine the characteristics of the distributions of gas and collisionless components (stars + dark matter, DM) after the interaction of two spheroidal galactic systems. We present calculations of the mass fractions of the gaseous and collisionless components lost by galaxies in the course of powerful interactions. The Smoothed Particle Hydrodynamics (SPH) method tracks the trajectory of each mass particle and this advantage makes it possible to estimate the mass of gas exchanged between colliding galaxies.
Figure 1. Collision scheme and geometric characteristics.

2. Mathematical and numerical models

Dark matter and stellar population are kinematically hot collisionless components, which requires the use of dynamic N-body models based on solving the following system of motion equations

\[
\frac{d^2 r_i^{(s)}}{dt^2} = \sum_{j=1, j \neq i}^{N_s} \frac{G m_j^{(s)} (r_i^{(s)} - r_j^{(s)})}{\left( |r_i^{(s)} - r_j^{(s)}|^2 + r_c^2 \right)^{3/2}} + \sum_{j=1}^{N_g} \frac{G m_j^{(g)} (r_i^{(s)} - r_j^{(g)})}{\left( |r_i^{(s)} - r_j^{(g)}|^2 + r_c^2 \right)^{3/2}} \quad (i = 1, \ldots, N_s),
\]

where \( G \) is the gravitational constant, \( N_s \) is the number of particles modeling stars and dark matter, \( N_g \) is the number of gas particles, \( N = N_s + N_g \), \( r_i^{(s)} \) is the radius vector of collisionless particles, \( r_j^{(g)} \) is the radius vector of \( j \)-th gas particle, \( m_j^{(s)} \) and \( m_j^{(g)} \) are masses of collisionless and gaseous particles, respectively. The cutoff radius of the gravitational potential at small radii \( r_c \) provides collisionlessness of particles that model the stellar and DM components [11, 12].

The gas components are described by the equations of hydrodynamics in the Lagrangian approach. We use the SPH method, for which the system of equations is:

\[
\rho_i = \sum_{j=1}^{N_n} m_j^{(g)} W \left( |r_i^{(g)} - r_j^{(g)}|, h_{ij} \right),
\]

\[
\frac{d\mathbf{u}_i}{dt} = - \sum_{j=1, j \neq i}^{N_n} m_j^{(g)} \left( \frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \mu_{ij} \right) \nabla W \left( |r_i^{(g)} - r_j^{(g)}|, h_{ij} \right) + \mathbf{f}_i,
\]

\[
\frac{d\varepsilon_i}{dt} = \frac{1}{2} \sum_{j=1, j \neq i}^{N_n} m_j^{(g)} \left( \frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \mu_{ij} \right) (\mathbf{u}_i - \mathbf{u}_j) \cdot \nabla W \left( |r_i^{(g)} - r_j^{(g)}|, h_{ij} \right),
\]

where \( N_n \) is the number of nearest neighbors particles, \( \rho_i, \mathbf{u}_i, p_i, \varepsilon_i \) are the density, velocity vector, pressure, specific internal energy of the \( i \)-th gaseous particle, respectively, \( \mu_{ij} \) is the artificial viscosity, \( W \) is the smoothing kernel function, \( h_{ij} \) is the smoothing length, \( \mathbf{f}_i \) is the total specific gravitational force on the \( i \)-th particle, determined from the right-hand side of equation (1) by replacing the indices \( (s) \leftarrow (g) \). Collisionless N-body model and Smoothed Particle Hydrodynamics provide a uniform modeling of the motion of multicomponent medium based on the Lagrangian approach [3, 13, 14]. Our earlier works [3, 13] contain a detailed description of the models and numerical methods. We use a direct method for calculating gravitational
forces (each particle interacts with each other particle), implemented as parallel CUDA code for computing system based on NVIDIA Tesla V100 GPUs, as well as an approximate classical TreeCode algorithm that is parallelized for use on GPUs.

Let us list the main input parameters that determine the characteristic features of the collision of two identical galaxies in our models:

(i) The relative velocity between two galaxies at large distances $V_{\text{coll}} = V_1 + V_2$ is the collision velocity (See Figure 1).

(ii) Relative mass of gas in the galaxy $\mu^{(\text{gas})} = M_g / M_s$ ($M_g$ is the total mass of gas, $M_s$ is the total mass of stars and dark matter).

(iii) The impact parameter $b$ is determined for the initial configuration when the distance between galaxies is $R^{(\text{init})}$ (See Figure 1).

It is convenient to characterize the result of interaction with the following integral characteristics:

(i) The dimensionless parameter $\beta^{(\text{loss})}$ determines the fraction of gas lost by both galaxies as a result of the impact events, $\beta^{(\text{loss})} = M_g^{(\text{loss})} / M_g$.

(ii) Part of the mass of the collisionless components ($M_s^{(\text{loss})}$) is also lost as a result of the interaction, to estimate which we use the parameter $\eta^{(\text{loss})} = M_s^{(\text{loss})} / M_s$.

(iii) The quantity $\beta^{(\text{exch})}$ characterizes the fraction of gas that one galaxy has captured from another galaxy.

(iv) There is a similar exchange of mass of collisionless matter $\eta^{(\text{exch})}$ in the process of interaction of two galaxies.

![Figure 2.](image)

Figure 2. An example of the interaction of two galactic systems with an impact parameter $b = 10$ kpc. All distances are in units of kpc. Left: initial distribution of surface density $\sigma_g$ ($t = 0, R^{(\text{init})} = 120$ kpc), white arrows show initial velocities; the time $t = 19 \rightarrow 1.8 \cdot 10^8$ yrs approximately corresponds to the main stage of the collision, when the centers of mass of the galaxies are at the minimum distance. Right: positions of large-scale shock waves in the inset on a large scale.
An important advantage of the SPH method is the ability to track the individual trajectories of movement of each particle, which allows us to determine the transition of matter from the gravitational well of one galaxy to another and calculate the parameters $\beta^{(\text{exch})}$ and $\eta^{(\text{exch})}$. This is fundamentally impossible for the Euler approach based on numerical grids.

3. Collision results: dependencies on geometric and kinematic characteristics

We have performed over 60 numerical experiments on colliding galaxies for various parameters such as $V^{\text{coll}}$, $\mu^{(\text{gas})}$, $b$, $N_s$, $N_g$ and for direct and TreeCode algorithms for gravitational forces. The figure 2 shows a typical interaction pattern. We use dimensionless parameters in numerical models, setting the gravitational constant $G = 1$, the initial radius of each galaxy before the collision $R_0 = 15$, the mass of the collisionless component $M_s = 100$ with the possibility of transition to physical quantities. For example, the choice of the parameters $R_0 = 15 \rightarrow 15 \, \text{kpc}$, $M_s = 1 \rightarrow 2.2 \times 10^9 M_\odot$ corresponds to the velocity $V = 1 \rightarrow 100 \, \text{km sec}^{-1}$.

![Graph showing the dependencies of gas and collisionless component mass loss on initial collision velocity](image)

**Figure 3.** Dependences of the fractions of gas ($\beta^{\text{(loss)}}$) and collisionless component ($\eta^{\text{(loss)}}$) lost by galaxies on the initial collision velocity $V^{\text{coll}}$ for impact parameters $b = 3$ (left), $b = 10$ (right) and for various methods for calculating gravitational forces.

Central collision ($b = 0$) has been studied in detail in [2, 3, 9, 10] and see references there in. Figure 3 shows the mass loss fractions for the gas and collisionless components for two values of the impact parameter $b/R_0 = 0.2$ and 2/3 for different initial collision velocities $V^{\text{coll}}$. The relative velocities of galaxies in clusters vary widely and can reach 2000 km sec$^{-1}$. Galaxies merge into one object at low collision velocities $V^{\text{coll}} < 3 - 5$, and high velocities ensure the preservation of two gravitational systems, which loses a part of its collisionless component ($\eta^{\text{(loss)}}$) and gaseous component ($\beta^{\text{(loss)}}$). Gas losses become large ($\beta^{\text{(loss)}} \rightarrow 1$) at high collision velocities and small impact parameters, which is due to the collisional nature of the gaseous component. The greatest mass loss of the collisionless component occurs at collision velocities, when there is a transition from major merging with the formation of one unified system to the scatter mode, when galaxies move away from each other (see solid black lines in the figure 3). The loss of stars and dark matter can reach 50 percent for critical regimes, and the escaping galaxies turn out to be heavily stripped during the interaction. The efficiency of these processes decreases with an increase of the impact parameter.
To control the results of the simulation, we use both the TreeCode with $\Theta = 0.5$ and the direct method for calculating the gravitational forces between the particles (“Direct” in the figure 3). The existing discrepancies between models are largely associated with the uncertainty of the choice of the sphere radius, which determines the outer boundary of the galaxy. An additional source of error for TreeCode is the large computational domain where particles are scattered, which requires large cell sizes arising from the hierarchical subdivision of space into cells at low particle concentration.

We compared the results of computational experiments based both on the direct method for calculating the gravitational force (Particle-Particle method, when each particle interacts with each), and very often used approximate TreeCode method based on hierarchical grids, which we implemented for GPUs (See Figure 3). The TreeCode algorithm is based on the multipole acceptance criteria $d > l/\Theta + \delta$ [15], where $\delta$ is the distance from the center of cell mass to the geometric center, $d$ is the distance from the particle to the center of cell mass, $l$ is the cell size, $\Theta$ is the opening angle ($\Theta = 0.5$), which determines the calculation error. TreeCode can lead to significant errors under some merging conditions, which is associated with wide scattering of particles, when the gravitational potential is determined by a very large spatial volume containing gravitating matter. The choice of a computational method can significantly affect the results of modeling multicomponent interacting systems. An additional complicating factor is the large difference between the integration time step for the collisionless component and the hydrodynamic step, which turns out to be very small.

**Figure 4.** Dependences of the fraction of matter ($\beta^{(\text{exch})}$ and $\eta^{(\text{exch})}$) exchanged between galaxies during interaction on the initial collision velocity $V^{\text{coll}}$. Left: impact parameter $b = 3$; right: $b = 10$.

We calculated the mutual exchange of mass due to the collision for various $b$ and $V^{\text{coll}}$ (figure 4). The capture of the collisionless component is very small and limited to a narrow range of collision velocity ($\eta^{(\text{exch})} < 0.01$). Mutual gas exchange can be more efficient and can exceed 10 percent with a small impact parameter.

### 4. Conclusion

Calculations are performed for the series of computational experiments for colliding spheroidal self-gravitating systems with different sets of physical characteristics. Variable parameters set
includes the relative masses of components, the size of galaxies, the collision velocity, the radial
profiles of matter density, the impact parameter. The initial equilibrium states of spheroidal
models of galaxies are in balance between self-gravity and pressure forces. Modeling collisions
with different sets of impact parameter and collision velocity shows that complex processes
occur, including the shock waves formation, scattering of gas and collisionless matter, associated
with the escape from the gravitational influence of galaxies. The main focus is on studying
the characteristics of the galactic systems and the surrounding intergalactic environment after
impact event.

The use of the Smoothed Particle Hydrodynamics method for modeling the gaseous
component makes it possible to estimate the mutual exchange of mass between colliding
multicomponent objects. These estimates strongly depend on the parameters of colliding
galaxies. In the future, it is planned to study collisions of unequal galaxies with different masses
and sizes.

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