Models For Simulating Galaxies Formation

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Abstract. Simulating galaxy formation in a cosmological context is one of the biggest challenges that astrophysics faces today due to the vast range of scales and numerous physical processes involved. Over the past few decades, with the improvement of the algorithm and the development of computer technology, the simulation of pure gravity from the initial tens of particles to the number of particles in parsecs, a large number of different numerical simulation techniques are used to study the formation and evolution of structures in the universe. During this process, the resolution and precision of numerical simulation are improved continuously, and the description of the physical process of baryonic matter in the model is becoming more and more perfect. This article introduces the research progress of the galaxy's formation. Firstly, the paper explains the principle of the. Then, it reviews the recent progress and main achievements of related models and numerical equations and analyzes the main problems and challenges faced at present. Lastly, it discusses the conclusion and prospects of galaxy formation.

Keywords: Galaxies formation, numerical simulations, galaxies evolution.

1. Introduction

The ultimate goal of cosmological simulation is to simulate the evolution of the entire universe through a few basic parameters, including the formation of planets, the birth of life, and the emergence of civilizations. But because of the power of computers, people are far from simulating all the details of the universe; Instead, they can only simulate astronomical phenomena, such as the formation and evolution of galaxies. But this is difficult enough, and even generations of astronomers have failed to solve some of the most basic problems: such as reconstructing the initial mass function of stars. Nonetheless, cosmological simulations have shown enormous power. The role of simulation in astrophysics and cosmology is more similar to the role of experiments in traditional physics: it can not only verify past hypotheses but also predict the future.

To improve the computational efficiency and scale of numerical simulations, people have tried to modify the way gravity is calculated. In 1980, Peebles adopted the non-collision collisionless Boltzmann equation to give the approximate form of Newtonian mechanics in cosmology, including the approximate equation of Newtonian dynamics and Poisson equation, and developed on this basis [1].

Two different numerical algorithms, the tree algorithm and particle-mesh (PM) algorithm, are proposed [2, 3]. Hence, a hybrid of the direct sum algorithm and the tree algorithm is derived, and a hybrid of the direct sum algorithm and the particle-mesh algorithm (particle-particle/particle-mesh, P3M) is derived [4]. Cosmological simulations that initially considered gas had only one-dimensional properties, with the gas and dark matter particles seen as being on a plane. This type of simulation can be used to study the formation of nonlinear structures under large-scale initial density perturbations and simply add the physical processes of gases to the model [5, 6].

Fluid dynamics has a good Lagrangian property, so people have added the smooth particle hydrodynamics (SPH) algorithm developed in the 1970s to the multi-body model [7]. The initial astrophysical SPH algorithm based on mass was developed. At the same time, since the fluid dynamics equation has the properties of the Euler equation, people have used the approximate method of solving the field dynamics quantity numerically by the Euler field equation and developed the Euler algorithm with space as the processing object [8].

The paper focus specifically on research progress in cosmological modeling of galaxy evolution. Chapter 2 will introduce the basic cosmological theory of numerical simulation and Chapter 3 will

focus on the numerical algorithm and dynamics basis of dark matter simulation. Chapter 4 covers dark matter and baryon simulations; Chapter 5 summarizes and looks forward to this research progress's prospects in the future.

2. Cosmological Context

2.1. Cosmological Model

Because the cosmos is expanding, cosmology is different from the simulation of structural mechanics, fluid mechanics, ocean dynamics, etc. Its coordinate system is a co-moving coordinate system that evolves - and it needs to choose an accurate cosmological model to describe this expansion. Most cosmological projects use the so-called "Standard Model of cosmology", the λCDM model: The cosmological constant Λ describes the dark energy that is responsible for the accelerating expansion of the universe, and the CDM (cold dark matter) refers to cold, non-collectible dark matter that is cold and has little random motion as it is decoupling from other matter. By observing the cosmic microwave background radiation, Planck Collaboration points out that dark energy accounts for about 70% and dark matter account for about 25% in the ΛCDM model, while the baryonic matter it can see only accounts for about 5% of the whole universe [9]. As for the curvature of space, researchers usually use flat space, which is both consistent with observation and easy to deal with.

Of course, some simulations also use other cosmological models, such as dark energy with different properties, dark matter with different properties, and gravity with different properties, which can solve some problems of the ΛCDM model at small scales to a certain extent, but usually bring other problems.

2.2. Initial Conditions

In addition to the cosmological model that describes inflation, another factor worth considering is the initial conditions. It is obvious that if all matter starts uniformly at rest, it will eventually collapse into a particle: this is not true. Inflation theory states that the original universe was not uniform but had small density perturbations that were subject to Gaussian random fields. In addition to density, how to set the initial position and velocity distribution of dark matter and baryonic matter, as well as the initial temperature distribution of baryonic matter, is also important.

3. Dark Matter Simulation

3.1. Dynamical Equations Of Dark Matter

For the ΛCDM model, dark matter accounts for the majority of the total matter, so most of the early simulation projects are pure dark matter simulations that only consider dark matter. The simple nature of cold dark matter makes it relatively easy to model, which is the real reason why earlier simulations only considered dark matter. Specifically, the collision cross-section of cold dark matter is so small that they can pass through each other and there is only gravitational interaction between them.

When it comes to gravity, most cosmological simulation projects use Newtonian gravity. Most matter in the universe travels well below the speed of light, so using Newtonian gravity is a very good approximation, and it makes the calculation much easier. But when considering extremely relative cases, like black holes or binary neutron star systems, it can have to use general relativity.

Thus, the evolution of dark matter in the ΛCDM model is attributed to the Vlasov equation of configuration space, such as collusion-free Boltzmann equation:

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + v \cdot \nabla_r f - \nabla_r \Phi \cdot \nabla_v f = 0 \quad (1)$$

And Poisson's equation:

$$\nabla^2\Phi = 4\pi G \int f d^3v = 4\pi G\rho \quad (2)$$

In Poisson's equation, f=f (r, v, t) Is the density distribution function of the dark matter in space-time, ρ=ρ (r, t) Is the density distribution function of position space, Φ=Φ(r) It's the gravitational potential.

3.2. Numerical Solution for Dynamical Equations of Dark Matter

Vlasov's equation is a special form of Liouville's equation, while Poisson's equation is equivalent to Newton's formula of gravity. Therefore, it can numerically solve the evolution of dark matter by solving the many-body gravity problem. Specifically, it can use discrete particles to represent continuous dark matter; These particles interact only gravitationally, and they move under the force of gravity. The key to the numerical solution is the trade-off between speed and accuracy. For the many-body gravity problem, the most direct method is to calculate the gravity of each dark matter particle from other particles in turn, and then calculate the acceleration, velocity change, and position change. The gravitational force calculated by this method is theoretically absolutely accurate, but it is too slow: if there are N dark matter particles in total, its computation is $O(N^2)$.

To improve speed, scientists have developed methods that sacrifice precision for speed, such as the tree algorithm [2]. The computation amount of these new methods is generally O(NlogN), which greatly improves the operation speed. In addition to the high computational speed, the error of its gravity can be limited by the number of levels of expansion, such as to the second level or higher. The calculation error of gravity can also be controlled by increasing the value of θ. Because the tree structure can cover the whole space, the algorithm can be flexibly applied to any aggregation structure and can automatically improve the resolution of the simulation. Because it does not have any geometric constraints, it can be combined with other integration methods. However, this algorithm has two major problems at the beginning, that is, it takes up a lot of storage space and cannot provide initial boundary conditions. With the development of computer hardware, the storage of data has been greatly improved, so the problem of storage space has been greatly improved. In addition, the problem of initial boundary conditions is also solved by other procedures such as Ewald summation [10].

3.3. Important Conclusions from Simulations of Pure Dark Matter

Under The standard cosmological model, which is the ΛCDM model, cosmological approximation based on Newtonian dynamics, using a Gaussian random field to describe the initial density fluctuations of matter, a numerical simulation of cosmology can be built to study the large-scale structure of the universe and the formation and evolution of galaxy clusters [1]. The simulation is mainly divided into two situations:

Many-body approximations of pure gravity. This treatment only takes into account the existence and gravitational effects of dark matter. In dynamics, the non-colliding Boltzmann equation and Poisson equation can be used to deal with the motion of particles. Due to the different methods of calculating gravity, the algorithm can be divided into direct and direct algorithms, tree algorithms, Particle-grid algorithms, and combinational algorithms [2, 4, 5, 11].

(2) Plus, the baryonic matter in the universe. The baryonic matter in the universe is generally regarded as an inviscid fluid. In terms of dynamics, the motion of particles can be described by the equations of classical fluid dynamics.

Depending on the object you are dealing with, you can divide the algorithm into two types:

The Lagrange algorithm, which takes the particle as the object, discretes the particle mass, and the SPH algorithm is the most commonly used one [7].

Eulerian/grid-based algorithm, in other words, the space is discretized by taking the space as the object, and the most common one is the adaptive mesh refinement (AMR).

3.3.1 Dark matter distribution on large scales

The large-scale structure distribution of dark matter is a network, which contains a large number of voids, walls, fibers, and dark matter halos. The large-scale distribution of dark matter obtained by pure dark matter simulations is surprisingly consistent with the observed results.

3.3.2 Dark matter halo mass function

If the density of the dark matter halo is regarded as a function of its mass, the evolution of the function with redshift z is obtained by pure dark matter simulation.

49.6% of all cells that are included in 18 million halos are above the detection limitation of 20 cells, and this is the most precise determination that dates the mass function of CDM halos. As Fig 1 shows, the function n (M, z) represents the M more massive than the density of halos. The fraction of mass limited by halos of more increases from 6.42×10^{-4} at z = 10.07 to 0.496 at z = 0.

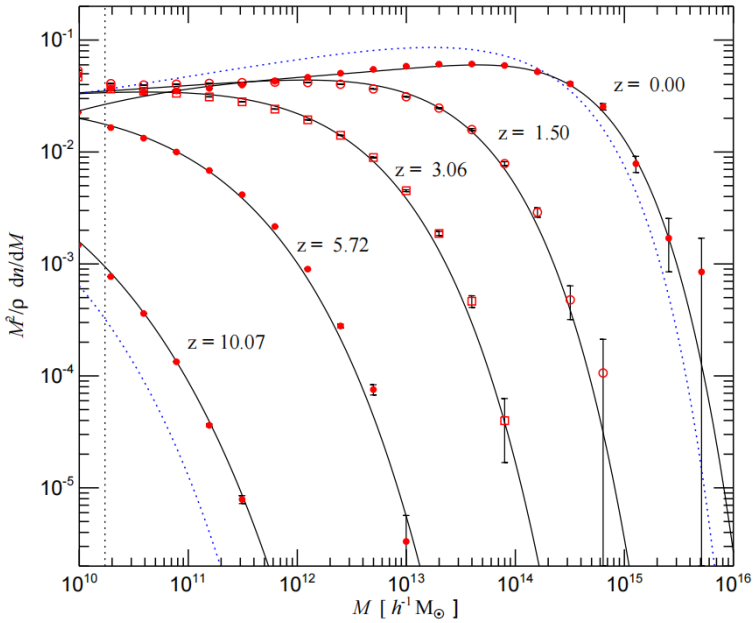


Fig. 1. Evolution of dark matter halo mass function with redshift in Millennium project [12].

4. Dark Matter and Baryon Simulation

With the development of computer power, pure dark matter simulations have become less satisfactory, after all, the universe is made of baryonic matter. So, they tried to introduce the 5% baryonic matter; But that 5% makes the cosmological simulation more than tenfold more difficult. However, compared with the benefits of introducing baryonic matter, the difficulty of ten times has not resisted the enthusiasm of astrophysicists.

4.1. Gas

Baryonic matter is mostly gas. The properties of gases are simpler than the other baryonic components, but they are also much more complex than cold dark matter: gas molecules can collide, so the interaction between gases is not only gravitational but also extrusion and viscous forces. Fortunately, the viscous force is generally negligible, and the gases in the universe can be regarded as ideal gases. Researchers often use fluid mechanics to describe the motion of gases in the universe, and two sets of equations can be established based on the Euler description and the Lagrange description. Similarly, based on these two descriptions, it also has two methods for solving equations of fluid mechanics numerically.

4.1.1 Euler description: adaptive mesh refinement

The Euler description is based on the description of the flow field of the control body. The shape and position of the control body are fixed, but the fluid can enter and exit the control body freely. It can describe the motion of the fluid by recording the mass and momentum of the fluid entering and leaving the control body.

Similarly, AMR divides the space into a rectangular grid, and it can track the flow of fluids in and out of each grid. These grids are the control bodies, and their shape and position are fixed. However, one of the characteristics of cosmological simulations is that the density distribution is extremely uneven, so it is not wise to apply the same dense grid all over space. It can increase the density of the grid in areas with high density or density gradient. For example, divide a cube lattice into eight identical small cube grids, each of which is half the length, width, and height of the original. So, it can double the resolution of the area. The process can continue subdivide some small cells into smaller cells. This is where the name comes from.

However, AMR also has drawbacks [8]. For example, it is difficult to achieve strict mass conservation, because the mass of each cell is constantly changing, and various rounding errors will cause the total amount to shift; It also does not satisfy the conservation of the Galilean transformation, that is, when the mesh is rotated at an Angle to simulate the same flow field, the AMR results will be slightly different.

4.1.2 Lagrange description: smoothed particle hydrodynamics

The Lagrange description is based on the description of the mass flow field. The mass itself has a fixed mass, but it will flow with the fluid; it can describe the motion of a fluid by recording changes in the position and velocity of the mass.

So, it can describe the motion of a fluid with a bunch of particles like cold dark matter. The particles here are no longer particles, but "smooth particles," which occupy a certain volume and are pushed against other particles. In a region of dense particles, the volume of each particle decreases, so the density increases — hence smoothed particle hydrodynamics (SPH)also can be used to describe density distribution and its heterogeneous cosmological flow field.

SPH solves the problem of mass non-conservation of AMR and the Galilean transformation non-conservation, but it also brings other problems: in fact, the shape of the mass body is constantly changing, but SPH treats it as a particle without shape characteristics, which leads to the error of SPH is generally large.

4.1.3 Other methods

Astronomers also use the moving grid method. Springel uses this approach in the cosmic fluid dynamics program Arepo: it is a variant of SPH, but Arepo does not consider fluid particles to be geometrically featureless; Arepo Voronoi splits the flow field based on the position of the particles, giving the fluid particles a cell-like geometry [7, 13]. Compared with traditional SPH, the moving grid method has higher accuracy, but its speed and stability are slightly inferior. To preserve the mass of each particle, Arepo had to make some tweaks so that it could not preserve the angular momentum of the system.

Hopkins proposed a moving grid method, GIZMO. This method is similar to Arepo, but it adopts a blurring treatment at the cell's boundary, which increases the cell's adjustability and avoids the problem of non-conservation of angular momentum [14]. As Fig 2 shows, the New Meshless Methods gives a blurrier demonstration and illustration of key conceptual differences between some of the methods. And basically, the Moving Mesh Methods (MMS) in the middle is one of the MFV method’s special cases.

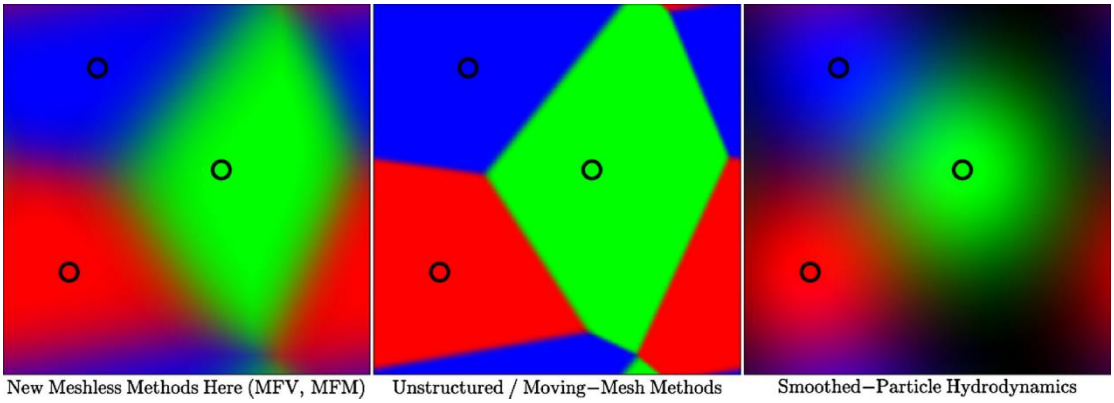


Fig. 2. The new meshless methods used by the GIZMO program (left), the moving grid used by the Arepo program (center), and the smooth particles used by the traditional SPH program (right) [7, 14].

4.2. Cooling Process

The reason why baryonic matter is more important at small scales is that cooling plays an indispensable role: when cold dark matter collapses, potential energy is converted into kinetic energy, which makes it difficult to continue to collapse; When baryonic matter collapses, potential energy is converted to kinetic energy (temperature increases), which is further dissipated through other processes (temperature decreases) - this cooling process allows baryonic matter to collapse continuously, thus dominating at small scales. However, the cooling process is very complex, collision excitation, ionization, inverse Compton scattering, and other processes will lead to the reduction of temperature. The simulation of cooling often adopts different models in different projects, which will not be detailed here.

4.3. Stellar

Because of the cooling process, the gas can keep collapsing and forming stars. An ideal simulation would be able to parse star formation, but there is not a fancy program for that. The highest resolved mass of large cosmology projects is much higher than the mass of a star (for example, the IllustrisTNG-100 baryonic particle has a mass of 1.4E6 times the mass of the Sun, which is already the mass of a giant molecular cloud), so it must use a specialized model to simulate star formation on a sub-scale. It is also important to note that the "star" here is not necessarily a star, but some compact objects smaller than the highest resolution, such as stars, black holes, star clusters, galaxies, and clusters of galaxies.

4.3.1 Stellar formation

The size of a star is so small compared to cosmological simulations that it can be treated it as a particle, so researchers often use particles to characterize stars. When the gas in a region meets the four conditions of low temperature, dense density, negative velocity gradient around the region, and self-gravitational confinement, it can generate a stellar particle in the region. If the stellar particle is very massive (For example, tens of thousands of times the mass of the Sun), then the particle represents many stars, so it can generate an "average stellar" particle here. However, suppose it is not very massive (For example, hundreds of times the mass of the Sun). In that case, the particle may represent only a few stars, and it needs to determine what these stars are: ordinary main sequence stars, supernovae, black holes, and so on.

4.3.2 Stellar feedback

Stellar feedback refers to the effect of the star on the surrounding material after its formation, including radiation, star wind, material jet, etc. Stellar feedback has been shown to play a very important role in the process of reionization and galaxy evolution. Most of the early simulations only considered feedback from type II supernovae, which are the most powerful feedback events in the

universe. Still, subsequent simulations also take into account feedback effects such as Type Ia supernovae, progressive giant branches, and binary neutron star mergers, which tend to release large amounts of heavy matter, greatly increasing the metallicity of the surrounding gas.

4.4. Other Methods

Important components of baryonic matter also include the interstellar medium, supermassive black holes, active galactic nuclei, magnetic fields, cosmic rays, radiation hydrodynamics, interstellar dust, heat capacity, viscosity, and other factors - enough to see the complexity of the baryonic matter. But like star formation, many of the components are the inevitable result of more fundamental physical processes, and the reason it has to model them is that researchers can't resolve them at current resolutions. I believe that with further advances in computer arithmetic, it can discard these unnecessary things and instead recreate the universe from a more fundamental perspective.

5. Conclusion

In conclusion, the study of galaxy formation through numerical simulations has made significant progress over the past few decades. From pure dark matter simulations to including baryonic matter, the models and numerical techniques have evolved to better capture the complexity of the universe and get more precise data.

There are also some limitations in this study. Although the ΛCDM cosmological model has been widely recognized, and by adding reliable physical models of galaxy formation, in which the important processes are various feedback effects, to the numerical simulation, the above problems can be corrected to a certain extent. However, due to the unknown nature of dark matter and dark energy, more accurate sky survey observations and numerical simulations based on various models are still needed to verify possible forms of dark matter and dark energy, and even modify gravitational models. It can be predicted that with the implementation of the next generation of large-scale sky surveys and the development of high-performance computer technology, cosmological numerical simulation will still be vigorously developed, and will play an important role in the study of dark matter and dark energy.

It is worth mentioning that reconstructing the cosmic field to obtain a structure consistent with the real universe under the constraints of observations, to study the formation and evolution of galaxies may be another important research direction.

Upcoming astronomical observation projects, such as the James Webb Space Telescope (JWST), the European Extremely Large Telescope (E-ELT), the Square Kilometre Array (SKA), and others, will provide unprecedented observation accuracy and depth. These facilities are expected to reveal more details about the formation of galaxies in the early universe, the history of cosmic reionization, and the distribution of dark matter.

At the same time, the exploration of the nature of dark energy remains a focus of cosmological research. Future research will focus on understanding how dark energy affects the accelerating expansion of the universe and how it relates to the overall structure of the universe.

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