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NUMERICAL SIMULATIONS OF GALAXY FORMATION

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ABSTRACT

The current status of numerical simulations of galaxy formation is reviewed. After a description of the main numerical simulation techniques, I will present several applications in order to illustrate how numerical simulations have improved our understanding of the galaxy formation process.

key words: galaxies: formation; galaxies: evolution; cosmology: theory; methods: numerical

1. INTRODUCTION

Understanding galaxy formation is a challenging problem whose solution will require a concerted effort combining observational, theoretical and numerical works. One of the most important progress in this area is probably the establishment of the cold dark matter (CDM) model which is currently the most popular scenario for structure formation. In this model, primordial fluctuations of density grow by gravitational instabilities to form the objects that we observe today. The important point is that this model predicts an hierarchical scenario for structure formation since the most massive objects (galaxy clusters) form from the accretion and mergers of smaller entities (galaxies). In this framework, galaxies are supposed to form when baryonic gas falls into the gravitational potential well of dark matter haloes. The gas initially heats up by shocks, cools radiatively, forming dense clouds which sink to the center of the halo and in which stars are formed.

These ab-initio models can be split in two major categories. On the one hand, numerical N-body simulations which model the dynamics and the interplay of these processes in detail. On the other hand, semi-analytical models (SAMs) describe the physical processes that affect the formation of galaxies by simple, physically motivated recipes. However, the boundary between these two categories is not very well defined. For example, hybrid models are commonly used in which the large-scale dynamics of the dark matter is modeled by simulation while SAMs are employed in order to populate dark matter haloes with galaxies. Also some commonly used star formation and feedback prescriptions in hydrodynamical galaxy formation models and recipes used in SAMs are very similar. In this review, I will focus on N-body simulation techniques.

2. N-BODY SIMULATION TECHNIQUES

The first application of N-body methods in astrophysics was for instance the simulations of galaxy clustering by Peebles (1970) using a very small number of particles. In these past decades, the methods have been continuously refined to allow simulations including more and more particles, able to resolve finer structures. Today, the biggest simulations (in terms of number of particles) use several billions particles (see for instance the Millennium simulation project[1]).

Broadly speaking, simulations can be roughly classified into two subgroups: (i) collisionless and (ii) hydrodynamical simulations. The basic idea is that dark matter and stars can be modelled as self-gravitating collisionless fluids, i.e. they fulfill the Vlasov equation. In general, it's very difficult to solve analytically such equation and then it turns out that N-body simulations provide a robust and efficient, although some-

[1] http://www.mpa-garching.mpg.de/galform/virgo/millennium/

times computationally expensive tool to numerically solve them. In other words, N-body simulations can be interpreted as a Monte Carlo approximation of the Vlasov equation. Now, if collisions between particles can no longer be neglected, the Vlasov equation must be replaced by Boltzmann equation. Then, a simple description of the intergalactic medium or the interstellar medium may be obtained by modeling it as an ideal mono-atomic gas. The gas is then governed by the continuity equation and the Euler equation. Here, we have to make the distinction between hydrodynamical simulation with and without star formation. Indeed, in simulations that include the effects of star formation, momentum and energy can be exchanged between the collisional (gas) and a collisionless (stars) component by processes other than gravity such as feedback mechanisms associated to star formation. Actually our understanding of the star formation process and its interaction with the surrounding interstellar medium is still rather limited. And in general, simulations used simple recipes similar to that outlined by Katz et al. (1992) namely the star formation rate is proportional to the local gas density divided by the local dynamical time scale.

2.1. Numerical Solutions

Gravity is supposed to be the dominant force at large scales and thus we cannot neglect gravitational forces due to distant particles. This makes calculation of force the most time consuming task in N-body simulations. As a result, a lot of attention has been focused on this aspect and many algorithms and optimizing schemes have been developed.

The most obvious approach to the problem of force calculation is to carry out a direct pairwise summation over all particles, called the Particle-Particle (PP) method, which is quite efficient for system with a small number of particles. However, the number of terms in the pairwise summation increases in proportion with N^2, where N is the number of particles. This rapid variation limited the early cosmological simulations to about 10^3 particles. It is also difficult to implement periodic boundary conditions in the PP method. These serious limitations have led to the development of more efficient methods such as the tree method. In this case, particles into groups are arranged in a tree structure: the simulation volume is taken to be a cube and is divided into smaller cubes at every stage till the smallest cells have only one particle in them. Larger cells can serve as groups of particles for a rapid calculation of force. Indeed, the force of a distant group of particles can be approximated by the force due to a single pseudo particle located at the center of mass of the group, with mass equal to the total mass of the group of particles. An essential ingredient is the criterion for deciding whether a group of particles can be considered distant or not. This is called the cell acceptance criterion and the error in approximation is controlled by the choice of this criterion. This approximation changes the scaling of the number of calculations from N^2 to $NlogN$. Although periodic boundary conditions are difficult to implement, tree codes have been used very effectively for cosmological N-body simulations.

Another method that has been used extensively for cosmological simulations is the Particle-Mesh (PM) method. It was the first method to be used for "large" (N$\sim 10^5$) simulations. In PM codes, the space is discretised on a mesh and, for the purposes of computing the gravitational potential, particles are assumed to be divided between the nearby vertices of the mesh. Finding the gravitational potential is easy, because the Poisson equation is trivial to solve by using the fast Fourier transform. However, PM codes cannot resolve structure at length scales smaller than a mesh. This seriously limits the effective dynamic range of simulations run with PM codes.

To improve these methods, several (hybrid) techniques have been proposed. For instance, in "Adaptive Mesh Refinement" (AMR) the grid is refined in high density regions. A new mesh with smaller spacing is introduced and the low resolution force calculated using the coarse global grid is improved upon using the refined mesh. Several levels of refinement can be introduced. We have also the P^3M method in which the basic idea here is to add a "correction" to the force computed using the PM method. This correction is computed by summing the contribution of close neighbors using the particle-particle method. In the same idea, the tree PM approach permit to split the gravitational force into a short range and a long range component.

As far as the hydrodynamic part is concerned, hydrodynamic methods used in cosmological simulations of galaxy formation can be classified into two primary classes: techniques using an Eulerian grid, including AMR techniques, and those which follow the fluid elements in a Lagrangian manner using gas particles, such as "Smoothed Particle Hydrodynamics" (SPH). SPH uses a set of discrete tracer particles to describe the state of a fluid, with continuous fluid quantities being defined by a kernel interpolation technique if needed (Lucy, 1977). Both of these methods have disadvantages that negatively impact their accuracy in certain situations, for example the suppression of fluid instabilities in the case of SPH, and the lack of Galilean-invariance and the presence of overmixing in the case of AMR. A novel scheme was recently proposed which is supposed to largely eliminate these weaknesses. It is based on a moving unstructured mesh defined by the Voronoi tessellation of a set of discrete points. The only numerical code for the purpose of galaxy formation studies is AREPO written by Springel (2010).

2.2. *Cosmolological - Idealized Simulations*

I will finish this part by saying a few words about the different approaches used to study galaxy formation. We have on the one hand cosmological simulations that describe the formation of a part of the universe (using a periodic volume) from high redshifts to present time. This permits to study several objects under their mutual influence while retaining the torques due to large scale structure. However, the mass resolution is often limited. Another approach is to create idealized simulations in which models are constructed on purpose to resemble observed galaxies, with a disk of gas and stars, eventually a stellar bulge, and always an extended, massive dark matter halo with structural properties (mass, spin, & density profile) consistent with the results of cosmological simulations describing the hierarchical growth of CDM haloes. These simulations have been intensively used to study the star formation properties in interacting systems as well as effects of feedback. Finally, the technique of "zoom" gather the advantages of these two approaches. In this case, haloes to be examined at higher resolution are selected from a large cosmological N-body volume. Successively finer resolution layers of dark matter are added to the initial conditions around the selected galaxy, until at the finest layer gas particles are also added. This technique permits to reach very high resolution in the simulated galaxy by taking into account the torques due to large scale structure, but at a much cheaper computational cost than if we were to run the entire box at the highest resolution.

3. APPLICATIONS

3.1. *The Structure of Dark Matter Haloes*

The increasing computer power and the advent of new simulation techniques allow to study the formation of individual dark matter haloes in full cosmological context. These advanced simulations addressed two of the key problems in cosmology. The first one concerns the sharp central density cusp in dark matter haloes, predicted by simulations and not seen in the rotation curve of bright spiral galaxies (see for instance Palunas & Williams, 2000). Navarro et al. (1996) found indeed that the density profiles of simulated dark matter are well described by a universal profile whose logarithmic slope tends to -2 at the origin while observations suggest a more flat profile. The second issue concerns the large number of subhaloes present in simulations but not observed (see for instance Kauffmann et al., 1993), as in the case of our Galaxy or M31, and referred to as the "missing satellite problem".

Could the discrepancies between observations and theory be related to our lack of knowledges about the star formation processes and the interaction between baryons and dark matter? Recent works based on hydrodynamical simulations suggest indeed that possible solutions can be proposed. For instance, the apparent suppression of cusp in the observational analysis of DM haloes profiles may come from the interaction between baryons and the DM component and proposed by different mechanisms. For example, the dark matter (DM) can be "heated" by the baryons by dynamical friction due to self-gravitating gas clouds orbiting near the center of the galaxy (El-Zant et al., 2001), by the evolution of a stellar bar (Weinberg & Katz, 2002), by the radiation recoil by a black hole (Merritt et al., 2004), by random bulk gas motions driven by supernovae feedback, recently suggested by Mashchenko et al. (2006) or by the bulk gas motion driven by an AGN activity (Peirani et al., 2008). Other mechanisms have been proposed such as the transfer of angular momentum from baryonic to dark matter (Tonini et al., 2006) or the expulsion of a large fraction of the gas due to feedback activities, causing the dark matter to expand (Gnedin & Zhao, 2002).

As far as the missing satellite problem is concerned, gas cooling can be partly prevented by photoionization process which may inhibit star formation in the majority of subhaloes. In this case, the dark matter satellites would be present, but only a small fraction of them would actually be visible, having formed stars prior to the reheating of the intergalactic medium (see for instance Bullock et al., 2000; Peirani, 2010).

3.2. *In the Galaxy Formation Process*

In this section I focus on two crucial aspects of galaxy formation within the CDM model: the role of interacting galaxy and the formation of disk galaxies.

3.2.1. *Galaxies-Interactions*

Simulating interacting galaxies is important in order to test theoretical ideas (hierarchical scenario), to gain insight into real systems and to constrain galaxy parameters (see for instance Peirani et al., 2009). In general, one of the main effects of a distant interaction or early stage merger is the central gas inflow. It increases the gas density, the gas clouds collision rate, so that any model for star formation will predict a significant increase in the star formation rate, or a so-called starburst. This has been extensively studied in simulations since the early 90s. In general, the starburst usually peaks in the early phases of the merger, near the first pericenter passage of a galaxy pair. A secondary but generally weaker burst can be triggered during the final coalescence. But more complex star formation rate evolutions can be obtained depending on the mass ratio of the system as well as the type of galaxies considered (Peirani et al., 2010). On the very central scales, the main consequence of galaxy interactions and mergers can be the growth of black holes. The interaction-driven gas inflows, that drive the central starburst, can fuel a central super massive central black hole (see for instance Di Matteo et al., 2005).

In the external structure, the tidal field and gravity torques generally lead to the formation of tidal tails. Other types of features can form in interactions such as collisional rings (in head-on collisions), polar ring or stellar shells and streams. All of these specific structures can be well reproduced by simulations which give precious clues of the formation of the host galaxies.

3.2.2. *The Formation of Disk Galaxies*

I will finish this review with the formation of disk galaxies which is one of the major unsolved problems of modern astrophysics. The basic theoretical framework states that disk galaxies arise from the gravitational collapse of a rotating protogalactic cloud of gas within the gravitational potential well of the dark halo. The gas cools via radiative processes during the collapse and eventually settles in centrifugal equilibrium at the center of the halo potential well forming a rotationally supported gas disk provided that some angular momentum is retained during the collapse. While N-body + SPH models have dominated the field of cosmological disk simulations to $z = 0$, significant progress has been made recently in running AMR models to z = 0 (e.g., Gibson et al., 2009). Now the state of art can be illustrated by the Mare Nostrum simulation[2] of the Horizon project.

Historically simulated disks have been too compact, too small overall in radius, and rotate too quickly at a given luminosity, making them unable to lie on the observed Tully-Fisher relation (see for example Steinmetz & Navarro, 1999). This problem has been termed the “angular momentum catastrophe” and it is significantly aggravated by another related problem, the “overcooling” problem. In the overcooling problem, baryons cool too quickly at early times and form dense clouds which sink toward the center of host haloes by experiencing dynamical friction. As a result, they have little angular momentum left by the time they arrive at the disk.

To solve this problem, the numerical resolution was first invoked. Indeed, in N-body + SPH simulations, the dark matter particles are typically an order of magnitude more massive than the gas particles. When a massive dark matter particle passes through a group of gas particles in the disk that have net rotation, there is a dramatic exchange of angular momentum in two body interactions. This increases the random motions of the disk particles and relaxes the disk into a more spheroidal distribution. Hydrodynamical simulations suggest that simulated disks with sizes comparable to observed disk sizes do not form until a minimum of $10^5 - 10^6$ particles is reached (see for instance Governato et al., 2004). But despite high resolutions, the simulated bulges of simulated galaxies are still much too large compared to the bulges of real disk galaxies. Then, to prevent the overcooling problem and its contribution to the angular momentum catastrophe, feedback mechanisms have traditionally been invoked. Feedback serves to prevent the rapid, early cooling of gas in simulated haloes. This heating also expel the gas at larger radius which increase its angular momentum.

[2] http://www.projet-horizon.fr/www.projet-horizon.fr /rubrique3.html

Feedback also plays an additional role in the creation of galaxy disks: the heating of the gas by feedback delays SF and keeps gas available until low redshifts. If the so called "cold flow" gas accretion in the early phases of galaxy formation (see for instance Dekel & Birnboim, 2006) does exist, a cold gas reservoir can be indeed built in the simulated galaxies. This point is crucial since it has been shown disks could be rebuilt during encounters of gas-rich spirals (see for instance Barnes, 2001). This result is contrary to the long held belief that mergers destroy existing disks. But it may reconcile the observations that suggest that disk galaxies represent the majority (70%) of the galaxy population observed in the local universe with the CDM model in which mergers and interaction of galaxies are an essential ingredient of galaxy formation and evolution.

4. CONCLUSIONS AND PERSPECTIVES

In the last four decades, the numerical simulation techniques have been considerably developed to provide deeper insight in the galaxy formation process. For instance, the development of pure dark matter simulations have permitted to constraint the inner structure of dark matter haloes supposed to host galaxies. But some of the theoretical predictions (central density cusp, large number of substructures) seem to be in disagreement with the observations. Before ruling out the CDM model, more complex and complete simulations are required. In particular, thanks to the increasing computer power, hydrodynamical simulations are henceforth an indispensable tool to describe all the relevant physical processes intervening in the long road leading to the formation of galaxies, searching for more realistic simulations whose results could be confronted with observations to be realized with future instruments dedicated to cosmology. During the next couple of years, these simulations are expected to resolve the finest structures (at the parsec scale) as well as to improve the description of black hole grow and AGN feedback which are among the biggest challenges of modern cosmology.

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