Numerical Simulations of Cosmic Structure Formation

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1 Introduction

Currently popular cosmological models predict that the cosmic structures evolved by gravitational instability from primordial density fluctuations generated through an inflationary epoch in the early universe. Results from recent CMB experiments gave strong support for this picture [1,2], and the ongoing two large galaxy redshift surveys, the Anglo-Austrian 2dF survey and the Sloan survey, are beginning to provide a large amount of data which will enable us to study extensively various properties of galaxies, clusters of galaxies, and QSOs.

Simulating the formation of these astrophysical objects within a cosmological context is a very difficult task, since it is a result of gravitational amplification of the initial matter density fluctuation (which must be solved accurately), together with the action of many physical processes such as gas dynamics, radiative cooling, photo-ionization, and radiative transfer. Although these physical processes seem to be too complex to allow for satisfactory numerical simulations, in recent years there has been a significant progress both in computer power and numerical methods. In the state-of-the-art simulations, some of the above listed physics are included self-consistently for 1D, 2D and a few particular 3D problems. Without being very optimistic, we may expect a simulation of galaxy formation in a cosmological volume with fully self-consistent treatments of important physics in a foreseeable future. Provided that we will soon have a definite cosmological model by measurements and determination of the fundamental cosmological parameters from high-precision observations, most notably new CMB experiments (e.g. MAP satellite mission), it is the time for numerical simulations to give an accurate prediction on the formation and evolution of large-scale *and* small-scale structure of the Universe. In this article I review some of the recent progress made in numerical simulations based on Cold Dark Matter models.

2 Large-scale structure

In a series of papers in late 80's, Davis, Efstathiou, Frenk & White [3] showed models based on Cold Dark Matter successfully reproduce a broad range of observations of large-scale structure of the universe. Their simulations, then the largest CDM simulation, employed (only!) 32^3 particles in a region of several tens of mega-parsec. Since then cosmological N-body simulations grew both in the number of particles and in simulation volume. Some of the cornerstones to list would be Gelb and Bertschinger's 1.7 million particles simulation, and a series of large simulations by the Virgo Consortium surveying several CDM variant models in the early and mid 90's. Finally in the past few years, progress in computational power achieved a highlight of such large numerical simulations; the Hubble Volume Simulations [5] employed 1 billion CDM particles and simulated a cosmological volume of $(3\ \mathrm{Gpc/h})^3$ region. A cubic region of $(3\ \mathrm{Gpc/h})^3$ covers a significant fraction of the observable universe, characterized by the Hubble radius, hence called the Hubble Volume Simulations. The large simulation volume necessitated to create a new type of outputs other than the normal 'snapshots' (=particles informations are dumped at a given cosmic time). The lightcone output, which explicitly and dynamically consistently takes into account the nonlinear gravitational evolution of the structure on the past lightcone of a hypothetical observer, made it possible to study various aspects of the formation and evolution of large-scale structure. Examples of studies making use of these outputs include clustering of galaxy clusters [6], the mass distribution of dark matter halos [7], the cosmological lightcone effect [8], mock galaxy redshift surveys [9], X-ray clusters [5], lensing the cosmic microwave background by large-scale structure [10]. These studies present many important predictions from the CDM models, which can eventually be tested against high-precision data from the 2dF, the Sloan survey, and also from deeper DEIMOS and VIRMOS surveys.

3 Crisis on galactic scales

Despite the success of the popular CDM models in reproducing the observed large-scale ($\gg 1$ Mpc/h) structure, the structure of nonlinear objects "dark halos" is still a controversial issue. Navarro, Frenk & White [11] claim, based on the results of their high resolution N-body simulations, that CDM halos have a 'universal' density profile which diverges toward the halo center with a slope of r^{-1} where r is the distance from the center. Recent higher resolution simulations confirmed their result and seem to suggest even steeper density profiles in the central regions. Observed rotation curves of several dwarf and LSB galaxies, however, appear to suggest that such dark matter dominated systems have soft, constant density cores. If such observations are confirmed by a higher resolution mapping of rotation curves [13], it apparently conflicts with the CDM prediction. There is also another often-claimed problem of over-abundance of subhalos [12].

Several mechanisms are proposed to resolve these problems. There are mainly two ways; one is to invoke hydrodynamic processes to blow gas out from small dark halos so that it makes such small systems literally dark, with a (somewhat optimistic) hope that a similar process might affect the distribution of dark matter in the center as well, and the other is to modify certain properties of dark matter. The latter possibility attracted a good deal of interests for the past few years (see the newly named dark matter candidates appeared on astro-ph in 2000-2001, from repulsive dark matter to fuzzy dark matter.) Warm dark matter [14], despite its weak point that there is no natural candidate within the standard particle physics, gives an immediate solution because, in warm dark matter models, the initial density fluctuations on small (galactic and sub-galactic) scales are suppressed. Suppression of small scale powers will solve the substructure problem, but appear to be unable to solve the density cusp problem. Spergel & Steinhardt [15] proposed that dark matter self-interaction might resolve both the density cusp problem and the over-abundance of subclumps, for elastic collisions of dark matter particles could lessen the central density and destroy low-velocity systems within a higher-velocity system. These plausible effects produce, however, a considerable problem in galaxy clusters. Yoshida et al. [16,17] carried out a set of numerical simulations of dark halo formation in a self-interacting cold dark matter model and concluded that the central cores in massive halos formed in the models are too large to be reconciled with the inferred core sizes from gravitational lensing observations. Meneghetti et al. [18] argued that observed large lensed arc systems put an upper constraint on the scattering cross-section of dark matter in clusters, essentially excluding self-interacting dark matter models unless the scattering cross-section is velocity dependent (decreasing with increasing velocity scale). Such possibilities of more complex scattering mechanisms might seem to viable, but now there are various constraints on the cross-section [19, 20, 21]. Given that the 'crisis on small scales' is not completely gone (in fact, it is not yet clear whether such crisis itself is real, rather than apparent), further theoretical and numerical works on the detailed structure of dark halos will greatly benefit. Also, hydrodynamic processes like supernova feedback remain to be examined whether they, singly or jointly, can suppress the formation of low mass galaxies.

4 Small-scale structure

In the bottom-up scenario of the CDM models, galaxies were assembled out of building blocks of stellar mass. The first gaseous objects in these models form at $z \sim$ 15-30 [22], soon after the collapse of dark halos of mass about $10^6 M_\odot/h$. At this early stage, the environment and the physics of the formation of the first small structure are simpler than those for, say, the present day star formation. Particularly the chemistry involved is much simpler in the absence of metals, and there is no radiation except the cosmic microwave background which is not important in structure formation at redshift $z \leq 100$. There have been already a few numerical simulation which incorporate the chemistry and the cooling of primordial gas [23, 24]. While these studies reveal some of the aspects of the first structure formation, they focus on the formation of a *single* object, and hence cannot tackle global aspects of the galaxy formation.

Perhaps more important informations can be obtained by a large simulation of evolution within cosmologically representative volume. Some of the outstanding issues to be envisaged then are (1) when exactly were the first stars formed ? (2) how small were such objects ?, and (3) what are the mass(es) of the dark halos which host such objects ? Answers to these questions will be the key to constrain the density fluctuations on small scales in the early universe and to better understand the physics of re-ionization. Next generation of observations such as NGST and ALMA, will be able to directly detect or even map the formation sites of the first small structure. There are a wide range of theoretical issues to address on the small-scale structure formation.

5 Summary

A wealth of data from ongoing large and/or deep galaxy redshift surveys will substantially improve our understanding of galaxy formation. High resolution numerical simulations will be a powerful tool to make accurate model predictions and test them against the observations. The computational techniques to treat dissipative processes are still in their infancy. In order to include them in high resolution N-body simulations, developing efficient and accurate algorithms to treat complex physics, most notably radiative transfer, will be an immediate task.

6 Reference

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