High-resolution numerical simulations for galaxy formation

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Abstract

Understanding of the structure evolution in the Universe has been greatly advanced with a rapid progress in high-resolution cosmological simulations. In this contribution, we report a new set of cosmological simulations with $512^3$ ($\sim 1.4 \times 10^8$) particles in a simulation box of $100 \, h^{-1}\text{Mpc}$. With this unprecedented resolution, we have successfully overcomed the over-merging problem while retaining a cosmological volume size that is crucial for the statistical analysis. The simulations are being applied to studying important astrophysical problems that are sensitive to the simulation resolution.

1. Introduction

Galaxy formation is one of the most important and most challenging problems in astrophysics. In the standard theories of galaxy formation, it is generally believed that the Universe is dominated by dark matter (DM), the early density perturbations generated in the inflationary era are amplified by gravitational instability, the DM halos form via the collapse of the high density regions, and galaxies are formed from the cooled gas within those DM halos.

The formation of DM halos, more generally the DM distribution on small scales, however, is a strongly non-linear problem. Direct numerical simulations provide the only reliable tool to approach this problem. Although there have been many exciting developments in analytical, semi-analytical or empirical modeling of the DM distribution, these results are generally calibrated with N-body simulations and their validity still depends heavily on the resolution of the simulations used.

In this contribution, we report a new set of cosmological N-body simulations that were obtained recently under a collaboration of Shanghai Astronomical...
Fig. 1. Dark matter distribution around the most massive halo in the LCDM100a simulation. The slice is $100\, h^{-1}\text{Mpc}$ wide and $10\, h^{-1}\text{Mpc}$ thick.

Observatory and the University of Tokyo. We use $512^3$ particles to simulate a Cold Dark Matter (CDM) model in a cosmological volume of $100(h^{-1}\text{Mpc})^3$. The simulations have achieved a mass resolution which is an order of magnitude better than the advanced simulations of the Virgo Consortium (Jenkins, A. et al. 1998) as well as our previous simulations (Jing & Suto 1998). They are now being applied to studying a number of astrophysical problems that are sensitive to the simulation resolutions. As their first application, we (Jing & Suto 2002) have studied the internal matter distributions within virialized halos and have successfully found an ellipsoid description for the halo density profile that is more accurate than the conventional spherical description.

2. N-body simulations

The simulations are generated with our Particle-Particle-Particle-Mesh (P$^3$M) code on the supercomputer VPP5000 at the National Astronomical Observatory of Japan. The code adopts the standard P$^3$M algorithm (Hockney & Eastwood 1981; Efstathiou et al. 1985), and is fully vectorized (Jing & Suto 1998), and has been recently parallelized. Each simulation uses $512^3$ simulation particles. Five simulations are generated for two representative cold dark matter (CDM) models of galaxy formation. The linear DM distribution in CDM models is completely specified by the density parameter $\Omega_0$, the cosmological constant $\lambda_0$, the shape $\Gamma$ and the normalization $\sigma_8$ of the linear power spectrum. Table 1 summarizes the physical and simulation parameters used for these simulations. The physical parameters are chosen so that the models are consistent with most
observations of the real Universe. A box size of $100 \, h^{-1}\text{Mpc}$ implies that the particle mass in this system is only $m_p \approx 10^9 h^{-1}M_\odot$. The force resolution is $\eta = 3 \sim 6 \, h^{-1}\text{kpc}$ (the Plummer form), so typical galactic halos can be well resolved. Each model (with one box size) will have a few different realizations in order to properly account for the cosmic variance (still in progress). One LCDM model uses a small force softening $\eta = 3 \, h^{-1}\text{kpc}$ and is evolved with 5000 time steps, so how the force softening affects non-linear structures of DM distribution can be checked. Therefore, these simulations will become an important source for studying galaxy formation, internal structures of DM halos, and nonlinear clustering of dark matter.

Table 1. List of simulations

| Model      | $N$  | $\Omega_0$ | $\lambda_0$ | $\sigma_8$ | $\Gamma$ | $m_p \, (h^{-1}M_\odot)$ | $L \, (h^{-1}\text{Mpc})$ | steps | samples |
|------------|------|-------------|--------------|-------------|----------|------------------------|------------------------|-------|---------|
| LCDM100a   | $512^3$ | 0.3         | 0.7          | 0.9         | 0.2      | $6.2 \times 10^8$        | 100                    | 5000  | 1       |
| LCDM100    | $512^3$ | 0.3         | 0.7          | 0.9         | 0.2      | $6.2 \times 10^8$        | 100                    | 1200  | 2       |
| SCDM100    | $512^3$ | 1.0         | 0.0          | 0.55        | 0.5      | $2.1 \times 10^9$        | 100                    | 1200  | 2       |
3. Preliminary results and future work

Figure 1 shows a dark matter distribution of the LCDM100a simulation centered at the most massive halo. The plot corresponds to a slice of $100\, h^{-1}\text{Mpc}$ wide and $10\, h^{-1}\text{Mpc}$ thick. Filamentary structures are very visible, as many previous studies of such simulations have discovered. More interesting features of the simulations are seen in Figure 2 which shows the DM distribution of the most massive halo. Substructures within the virialized region are preserved well, similar to high-resolution simulations for individual halos (Moore et al. 1999), therefore the over-merging problem encountered in previous studies of cosmological N-body simulations has now been successfully resolved in our simulations. This will be very important to studying the dynamical properties and spatial distribution of galaxies when using the simulations (e.g. based on the semi-analytical modeling).

With this large set of high-resolution simulations, many interesting cosmological problems will be investigated. As an “incomplete” list, we are 1) studying the DM distribution in the strongly clustering regimes; 2) analyzing internal structures of DM halos; 3) investigating galaxy formation by hand-inputing gas physics; 4) applying the simulations to real observations.

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