Cosmic Structure Formation and Dynamics: Cosmological *N*-body Simulations of Galaxy Formation and Magnetohydrodynamic Simulations of Solar Atmosphere

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Cosmological *N*-body simulations have been carried out by applying an AMR (Adoptive Mesh Refinement) *N*-body code implemented to the Earth Simulator. Numerical simulations using 1024^3 particles produced more dark matter clumps (dark matter halos) in the mass range $10^{10}M_{sun} < M_h < 10^{11}M_{sun}$ than previous simulations using 512^3 particles. By identifying each dark matter halos from the output particle data, we obtained a merger history tree of dark matter halos. Using the merger trees and a semi-analytic model of galaxy formation, we are making a numerical galaxy catalog by computing the observable quantities of galaxies imbedded in the dark matter clumps. We also performed three-dimensional magnetohydrodynamic simulations of the solar atmosphere to pin-down the physical mechanism of coronal heating and solar wind acceleration. We found that almost horizontal magnetic loops are created in the upflow regions of the convection. Such small-scale, convectively-driven emergences of horizontal fields have actually been observed by Japanese satellite Hinode.

Keywords: Astrophysics, Galaxy Formation, Magnetohydrodynamics, Solar Activities

1. Introduction

Cosmic structures such as galaxies are formed by the growth of primeval fluctuations through the gravitational attraction between matters, more than 80% of which are invisible matter called dark matter. Currently popular scenario of structure formation is the hierarchical clustering scenario, in which structures are formed through merging of smaller sub-structures. These condensations consist of invisible dark matter and gas confined in the gravitational potential of the dark matter clump.

The formation and evolution of dark matter clumps can be studied by gravitational *N*-body simulation. Yahagi and Yoshii [1] developed a cosmological *N*-body code based on a Particle-Mesh (PM) method and implemented it to the Earth Simulator. High spatial resolution is achieved by introducing the adaptive mesh refinement (AMR) technique, which subdivides meshes where higher resolution is required. Using this code, we carried out 1024^3-particle cosmological *N*-body simulation. Numerically obtained mass distribution of dark matter clumps and the merging history of each clump can be used to make a numerical galaxy catalog which enables us to directly compare the galaxy formation models and observational data.

We also present the results of three-dimensional magnetohydrodynamic (3D MHD) simulations of the solar atmosphere covering the region from the upper convection zone to the corona. Numerical results can be compared with the unprecedented high-resolution observations of the solar atmosphere by Hinode satellite. These studies are now revealing how magnetic energy is transported from convection zone to the corona, and why high temperature corona exists above cool photosphere/chromosphere.

2. Gravitational *N*-body Simulations of the Formation of Dark Matter Clumps

2.1 Numerical Method

In the gravitational *N*-body code based on the PM method, gravitational force is calculated as follows: 1) Density at grid points is obtained by assigning mass of particles to the neighboring grids. 2) Gravitational potential at grids is derived from density at grids by a discrete Poisson solver. 3) Gravitational force at grids is derived by differentiating the potential at grid points. 4) Gravitational force on particles is computed by interpolating the gravitational force at nearby grids. In the PM method, resolution of gravitational force is limited by the mesh spacing. We overcame this defect by the adaptive mesh refinement (AMR) technique which places finer meshes where higher resolution is required [1].

Our AMR *N*-body code has been optimized for distributed memory type parallel computers. Details of the vectorization and the parallelization of the code are given in Yahagi [2]. We have tuned our code for the Earth Simulator. We achieved 99.201% vectorization ratio, and 99.9777% parallelization ratio derived by the comparison between 64 nodes and 128 nodes simulations. At the initial state, white noise fluctuation is imposed for the density.

2.2 Result of the Simulation using 1024^3 Particles

We carried out a cosmological *N*-body simulation using the AMR *N*-body code implemented to the Earth Simulator. The model parameters are $(h, \Omega_d, \Omega_b, \Omega_v, \sigma_8) = (0.7, 0.252, 0.048, 0.7, 0.9)$, where h is the Hubble constant normalized by 100 km/s/Mpc. The density of dark matter, baryon, and vacuum normalized by the critical density are denoted by Ω_d, Ω_b, and Ω_v, respectively. σ_8 is a normalization of the power spectrum of the initial density fluctuation. The box size of the simulation is 100 Mpc.

Figure 1 shows the column density of the dark matter particles at current epoch ($z = 0$). Left panel shows the entire simulated region. Middle and right columns represent the magnified map of the simulated region.

Top, middle, and bottom rows show a cluster of galaxy, a group of galaxy, and a galaxy, respectively.

2.3 Mass Function of Dark Halos

Using the $N = 1024^3$ simulation data, we derived the mass function of dark halos, or mass dependence of the number density of dark halos. Dark halos are selected by the Friends-of-friends method from the output data. The result is shown in Fig. 2. The mass function of $N = 1024^3$ simulation is represented by open circles. For comparison, the mass function

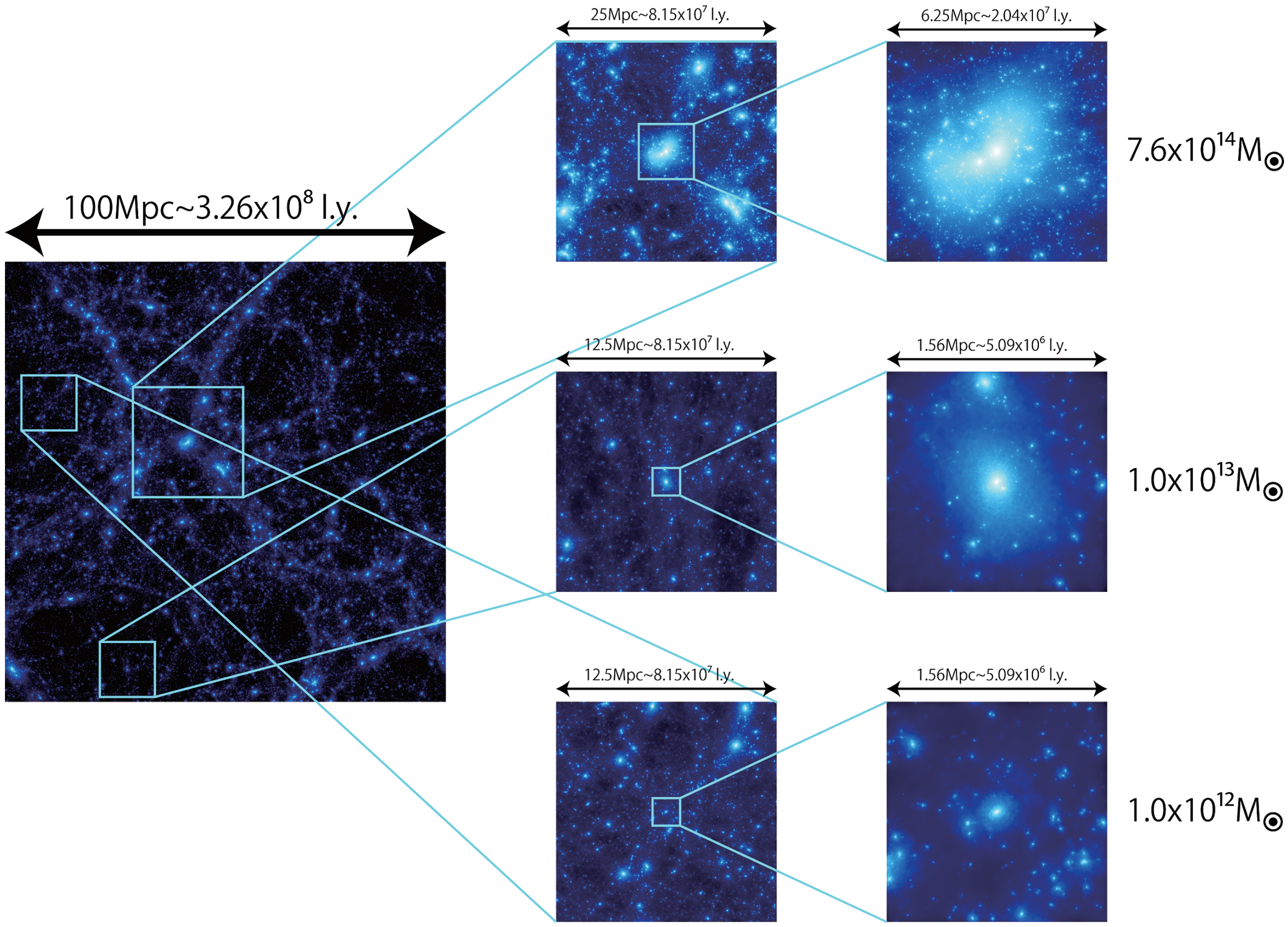

Fig. 1 Snapshot of the cosmological *N*-body simulation at $z = 0$, or current epoch. The left panel shows the distribution of particles in the whole simulated region. The box size of the simulation is 100 Mpc, or about 326 million light year. The middle and right column panels show the magnification of the left panel. The magnification level increases from left to right. The top row panels show the dark halo of a cluster of galaxies whose mass is 7.6×10^{14} M_{sun}, where M_{sun} is the mass of the sun. The middle and bottom row panels show dark halos of a group of galaxies whose mass is 1.0×10^{13} M_{sun}, and of a galaxy whose mass is 1.0×10^{12} M_{sun}, respectively.

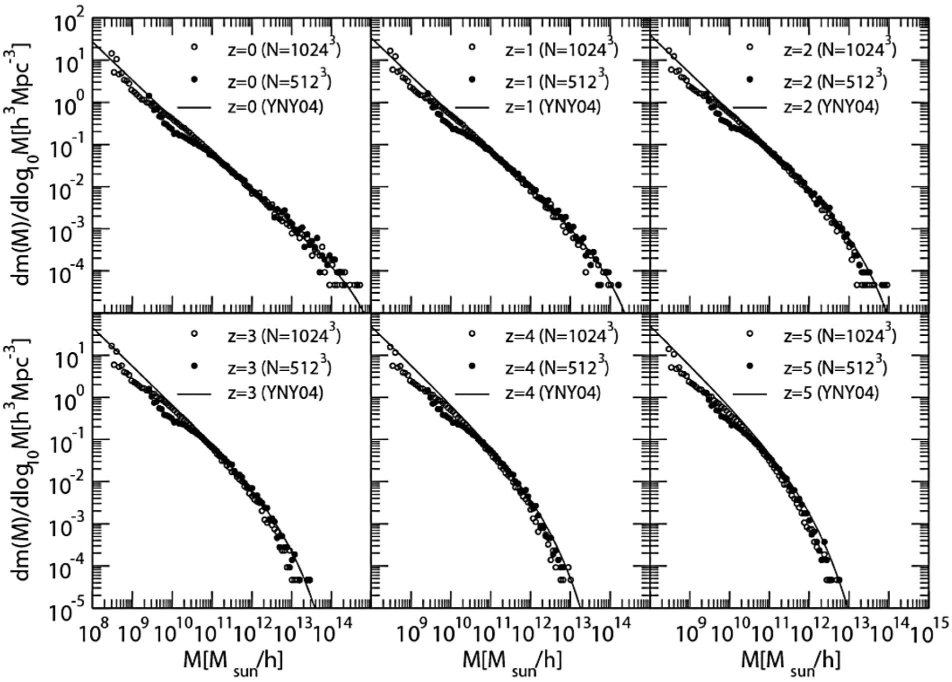

Fig. 2 Mass function of dark halos at various epochs. In each panel, open circles and filled circles represent the mass function from simulations of this work (N = 1024^3), and a previous work (N = 512^3), respectively. Solid curves show the fitted mass function from Yahagi, Nagashima, and Yoshii [3]. The epochs are z = 0, 1, 2, 3, 4, and 5, from left to right and top to bottom. There are more halos in the N = 1024^3 simulation in the mass range between $10^{10} < M_h/M_{sun} < 10^{11}$ than those in the N = 512^3 simulation.

obtained from an N = 512^3 simulation (filled circles) and an analytic fitting function (solid line) are also shown. There are more number of halos in the N = 1024^3 simulation in the mass range between $10^{10} < M_h/M_{sun} < 10^{11}$ than those in the N = 512^3 simulation. This may be caused by the increased mass resolution of the N = 1024^3 simulation.

2.4 Numerical Galaxy Catalog

We are making a mock catalog of galaxies using the N = 1024^3 simulation data. The mock catalog, named the Numerical Galaxy Catalog (νGC) is produced as follows: First, dark matter clumps (dark halos) are extracted from all output particle data. Then dark halos at an epoch are associated with dark halos at the next epoch, and we obtain merger history tree diagram of dark halos at the current epoch. Finally using this merger trees and a semi-analytic model of galaxy formation, we calculate the observable properties of galaxies in dark halos. Details of the νGC is described in Nagashima et al. [4], where the N = 512^3 simulation data was used. Because of increased mass resolution, νGC with the N = 1024^3 simulation data may predict properties of galaxies better especially for dwarf galaxies whose mass is smaller than normal galaxies.

3. Magnetohydrodynanical Simulations of Solar Convection Zone and Corona

The outer atmosphere of the Sun, called solar corona, is hotter than the photosphere, the visible surface of the Sun. Temperature of the corona is as high as 1 million K whereas that of the photosphere is about 6000 K. From the corona, plasma is continuously flowing out against solar gravity into the interplanetary space. This mass outflow is called solar wind. Coronae (hot atmosphere) and winds (mass outflow) are commonly observed in various stars and other astronomical objects, and the mechanism that heats the coronae and so accelerates the winds have been a long-standing problem in astrophysics.

In late-type stars such as the Sun, the energy source of coronal heating and wind acceleration is believed to be convective motion in the photosphere. The Poynting flux generated by the interaction of the convection and the magnetic field is then transported either by MHD waves or by current sheet formation and dissipated in the corona. Which process becomes dominant is determined by spectrum of the magnetic disturbances. High frequency disturbances result in MHD waves, and low frequency disturbances result in current dissipation. Since the spectrum of the magnetic disturbance is determined by the dynamics of convection, which in turn is affected by the presence of magnetic field, self-consistent simulation of magneto-convection and upper corona is essential to pin-down the physical mechanism of coronal heating and wind acceleration.

Toward this end, we performed 3D MHD simulation that spans a region running from the upper convection zone up to corona. The size of the simulation domain is 20000 km in horizontal directions and 40000 km in vertical direction, which is resolved by 700 × 700 × 300 grid points. At first we ran the simulation without magnetic field until convection fully developed and the system reached a quasi-steady state. Then we imposed a vertical and uniform magnetic field and continued calculation. We intend to change the strength of imposed magnetic field to study various regions of the Sun. However, simulation for one parameter requires more than a few thousands node hours by the Earth simulator. Due to the limited computational resource, so far we could successfully run only one simulation corresponding to solar "plage" region, where average magnetic field is about 100G (stronger than the quiet Sun but weaker than sunspots).

Figure 3 shows a three-dimensional visualization of the simulation result. The horizontal slice represents the photosphere. The gray scale on the slice indicates vertical velocity showing the convection motion; light is upflow and dark is downflow. Also shown is the magnetic field lines integrated from uniformly distributed points at a certain height in the corona. Even when the initial magnetic field is vertical and uniform, the magnetic field in the photosphere and below becomes highly disordered. In addition to the vertical flux concentrated in the downflow regions, low-lying, almost horizontal magnetic loops are seen in the upflow regions. The origin of these horizontal fields is the disordered fields in the convection zone that are driven by the convective upflows to emerge above the photosphere.

Recently, such small-scale, convectively-driven emergences of horizontal fields have actually been discovered by the Solar Optical Telescope of Hinode satellite [5]. Isobe et al. (2008) pointed out that the small-scale emergences may play important role in coronal heating and solar wind acceleration via magnetic reconnection with the vertical fluxes [6]. Note that the small scale horizontal fields have not been considered in previous coronal heating theories. Detailed comparison of the large-scale simulation results from Earth simulator with the Hinode observation is beginning to be conducted in order to reveal the role of horizontal field in coronal heating.

4. Summary

We reported the results of cosmological *N*-body simulation of the formation of dark matter clumps and three-dimensional MHD simulation of magneto-convection in the solar atmosphere. The mass distribution of dark matter clumps obtained by $N = 1024^3$ particle simulation produced more dark matter clumps in the mass range $10^{10}M_{sun} < M_h < 10^{11}M_{sun}$ than previous simulations using 512^3 particles. The simulation result is now used to make a numerical catalog of galaxies to statistically compare the numerical results with observations.

We also performed three-dimensional MHD simulations of the solar atmosphere to pin-down the physical mechanism

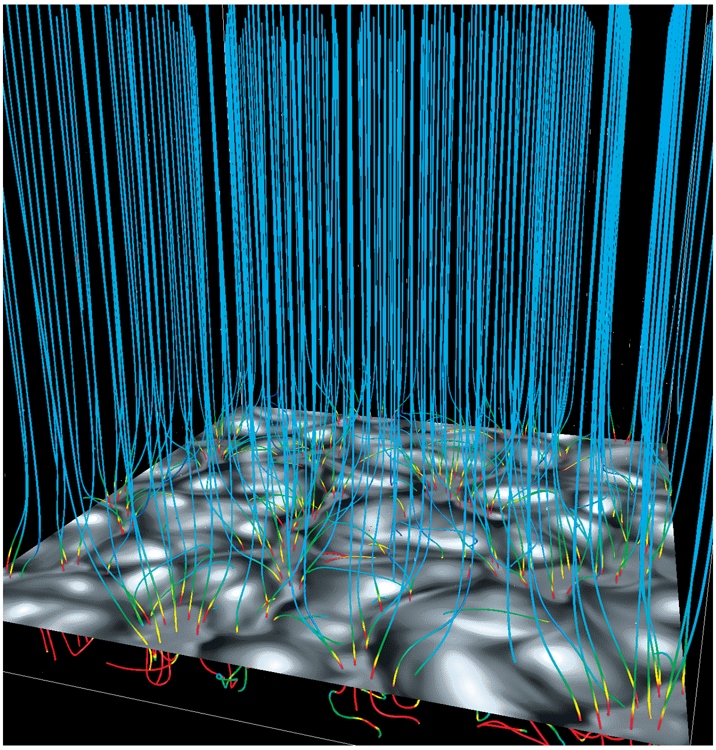

Fig. 3 Snap shot of the result of the 3D MHD simulation of the solar atmosphere. The horizontal slice shows the vertical velocity of convective motion in the photosphere. The color of the magnetic field lines indicates the field strength.

of coronal heating and solar wind acceleration. We found that almost horizontal magnetic loops are created in the upflow regions of the convection. Numerical results will be compared with the observations of the Hinode satellite.

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宇宙の構造形成とダイナミックス：銀河形成のN体シミュレーションと太陽大気の磁気流体シミュレーション

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地球シミュレータに実装した解適合格子(AMR)法に基づくN体シミュレーションコードを用いて1024^3粒子を用いた宇宙の大規模構造と銀河形成のシミュレーションを実施した。宇宙膨張開始後、現在に至るまでのシミュレーションが完了し、形成されたダークマター塊の質量分布を求めることができた。粒子数が増えたことにより10^{10}～10^{11}太陽質量の矮小銀河を分解できるようになり、この質量範囲のダークマター塊の割合が512^3粒子を用いたシミュレーションに比べて増加した。シミュレーション結果を基にしてダークマター塊の合体の系譜を辿り、銀河形成の準解析的モデルを適用することによって、これらのダークマター塊の中に形成される銀河の観測的特徴を求めてカタログ(数値銀河カタログ)を作成する作業を進めている。太陽グループでは太陽対流層上部からコロナを計算領域に含めた3次元磁気流体シミュレーションを実施し、鉛直上向きの対流運動が発生している領域で水平磁場が浮上してくることを見出した。このような水平磁場浮上は太陽観測衛星「ひので」による高解像度観測でも観測された。浮上水平磁場と鉛直磁場のリコネクションがコロナ加熱と太陽風加速に重要な役割を果たしている可能性がある。シミュレーション結果と「ひので」衛星による観測結果を詳細に比較する研究を進めている。

キーワード：宇宙物理学, 銀河形成, 磁気流体力学, 太陽活動