Cosmic Structure Formation and Dynamics: Cosmological N-body Simulations and Magnetohydrodynamic Simulations

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By applying a cosmological *N*-body code implemented to the Earth Simulator, we are carrying out numerical simulations of the formation of galaxies and the large-scale structure of the universe. Such simulations designed for making a numerical galaxy catalog, enable direct comparison between galaxy formation models and observational data. High-resolution global simulations of black hole accretion disks are carried out by using a three-dimensional magneto-hydrodynamic (3D MHD) code in Cartesian coordinates. They confirmed that amplification of magnetic energy inside the disk saturates when the magnetic energy is about 10% of the thermal energy. In high temperature disks, one armed spiral density enhancements are formed inside the disk. The efficiency of angular momentum transport increases with disk temperature. Preliminary results of 3D MHD simulations of magneto-convection and energy transport in the solar atmosphere are presented.

Keywords: Astrophysics, Galaxy Formation, Magnetohydrodynamics, Accretion Disks, Solar Activities

1. Introduction

Numerical simulations enable us to study how cosmic structures are formed from primeval fluctuations. Fluctuations grow through the gravitational attraction between matters, most of which are invisible dark matters. 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 are carrying out a 1024^3-particle cosmological *N*-body simulation, which is the largest simulation designed for statistical study of galaxies, to make a numerical galaxy catalog which enables direct comparison between galaxy formation models and observational data.

During the formation of galaxies, magnetic fields are amplified and begin to affect the dynamics of ionized gas in galaxies. Global three-dimensional magnetohydrodynamic (3D MHD) simulations of galactic gas disks revealed that magnetic fields are amplified to μG by magneto-rotational instability (MRI). The buoyant escape of the magnetic flux from the disk to the disk halo drives quasi-periodic reversal of galactic magnetic fields [2]. Similar magnetic activities take place in accretion disks formed around a gravitating object. Machida *et al.* [3] studied the evolution of an accretion disk by global 3D MHD simulations and showed that the growth of MRI saturates when the magnetic energy becomes about 10% of the thermal energy (i.e., $\beta = P_{gas}/P_{mag} \sim 10$). Accretion disks sometimes show sawtooth-like oscillation by repeating the accumulation and release of magnetic energy [4]. Magnetic reconnection taking place in the innermost region of black hole accretion disks produces flare like activities observed as X-ray shots [5]. In section 3 of this report, we present the results of high-resolution global 3D MHD

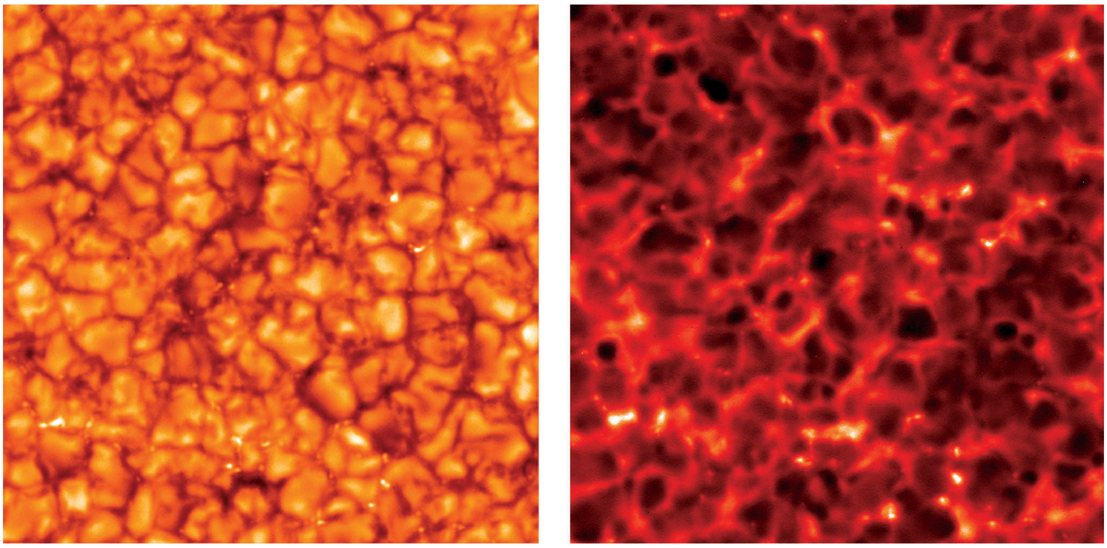

Fig. 1 High resolution images of the solar atmosphere obtained by the optical telescope aboard the HINODE satellite (provided by National Astronomical Observatory, http://solar-b.nao.ac.jp/news/061127PressConference/). The left panel shows the G-band (430nm) image of the photosphere. The right panel shows the Ca H line (397nm) image of the chromosphere.

simulation of an accretion disk using Cartesian coordinates.

It has been recognized that magnetic fields are driving various activities of the Sun such as flares, jets, and coronal mass ejections. In September 2006, a new solar satellite HINODE was successfully launched. Figure 1 shows the image obtained by the optical telescope aboard HINODE, which enables unprecedented high-resolution observation of the solar atmosphere. The optical telescope clearly resolves convective cells (granulations) and energy release in their boundaries. In section 4, we present preliminary results of 3D MHD simulations of magneto-convection. By comparing the HINODE observations and numerical simulations, we will be able to reveal how energy is transported from the photosphere to the corona, and answer the long standing question why high temperature corona exists above cool photosphere/chromosphere.

2. Gravitational *N*-body Simulations of Cosmic Structure Formation

2.1 Numerical Method

Our simulation is carried out with an *N*-body code based on the Particle-Mesh (PM) method. While the direct summation force calculation costs O (N^2) computation, time complexity of the PM method is O (N). In the PM method, gravitational force is calculated according to the following steps: 1) Mass of particles is assigned to the neighboring grids. 2) Potentials at grids are derived from density at grids by a discrete Poisson solver, such as the multigrid method. 3) Gravitational forces at grids are derived by subtracting potential at grids. 4) Gravitational forces on particles are derived by interpolating the gravitational force at nearby grids. As we mentioned, time complexity of the PM method is O (N). However, in exchange, resolution of gravitational force is limited by the mesh spacing in the PM method. We overcame this defect of the PM method by the adaptive mesh refinement (AMR) technique which places finer meshes where higher resolution is required [1].

2.2 Code Optimization

The mass assignment part (step 1 in the previous subsection) of the PM method is hard to be vectorized. However, including that part, our AMR *N*-body code is optimized for vector-type supercomputers. The basic strategy is as follows: First, particles are sieved into cells, thus, particles are linked listed from the cell which includes them. If we trace these linked lists, such loops are not vectorizable. Instead of doing that, we trace the first linked lists by one step, then trace the next linked lists by one step, and so forth. Such loops are vectorizable.

We also parallelized our AMR code for distributed memory type parallel computers. First, we sort the hierarchical mesh data by the Morton ordering level by level. Then we decompose and distribute the sorted mesh among processes. Particles are also distributed among processors. The processor to which a particle is allocated must be also responsible for the finest cell which contains the particle. Details of the vectorization and the parallelization scheme of our AMR *N*-body code are given in Yahagi [6].

Finally, 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. Initial condition was a white noise initial density fluctuation and consists of 1024^3 particles.

We are now carrying out a concordance cosmological simulation. The adopted cosmological parameters are $(h,\Omega_d,$

Ω_b, Ω_v, σ_8) = (0.7, 0.252, 0.048, 0.7, 0.9), here h is the Hubble constant normalized by 100 km/s/Mpc. Ω_d, Ω_b, and Ω_v are density of dark matter, baryon, and vacuum, respectively, normalized by the critical density. σ_8 is a normalization of the power spectrum of the initial density fluctuation. The box size of the simulation is 100 Mpc, and the number of particles is 1024^3=1,073,741,824. The simulation is now ongoing and we show the snapshot from the latest data in Fig. 2. Time from the beginning is about 3.5×10^9 years, which corresponds to the epoch about 10^{10} years ago, i.e. red-shift is about 1.8.

The upper left panel shows the whole region, and other panels show the magnification of it centered on a group-sized halo. Magnification level increases in clock-wise direction. As shown in the lower left panel, a group of galaxies already has a halo.

3. Global Three-dimensional Magnetohydrodynamic Simulations of Accretion Disks

By using the 3D MHD code CANS (Coordinated Astronomical Numerical Software) implemented to the Earth Simulator, we carried out global 3D MHD simulations of a gas torus initially threaded by weak azimuthal magnetic fields. We adopted Cartesian coordinates instead of cylindrical coordinates to avoid the singularity at the rotation axis and short time steps near the rotation axis imposed by the Courant condition. General relativistic effects are simulated by using the pseudo Newtonian potential $\Psi = -GM/(r-r_s)$ where r_s is the Schwarzschild radius. Absorbing boundary condition is applied at $r=2r_s$ and $R=(x^2+y^2)^{1/2}=100r_s$. The initial state is a constant angular momentum torus whose density maximum is at 10 r_s for model A and B, and 20 r_s for model C. The initial ratio of gas pressure to magnetic pressure is 100. The initial ratio of thermal energy to gravitation-

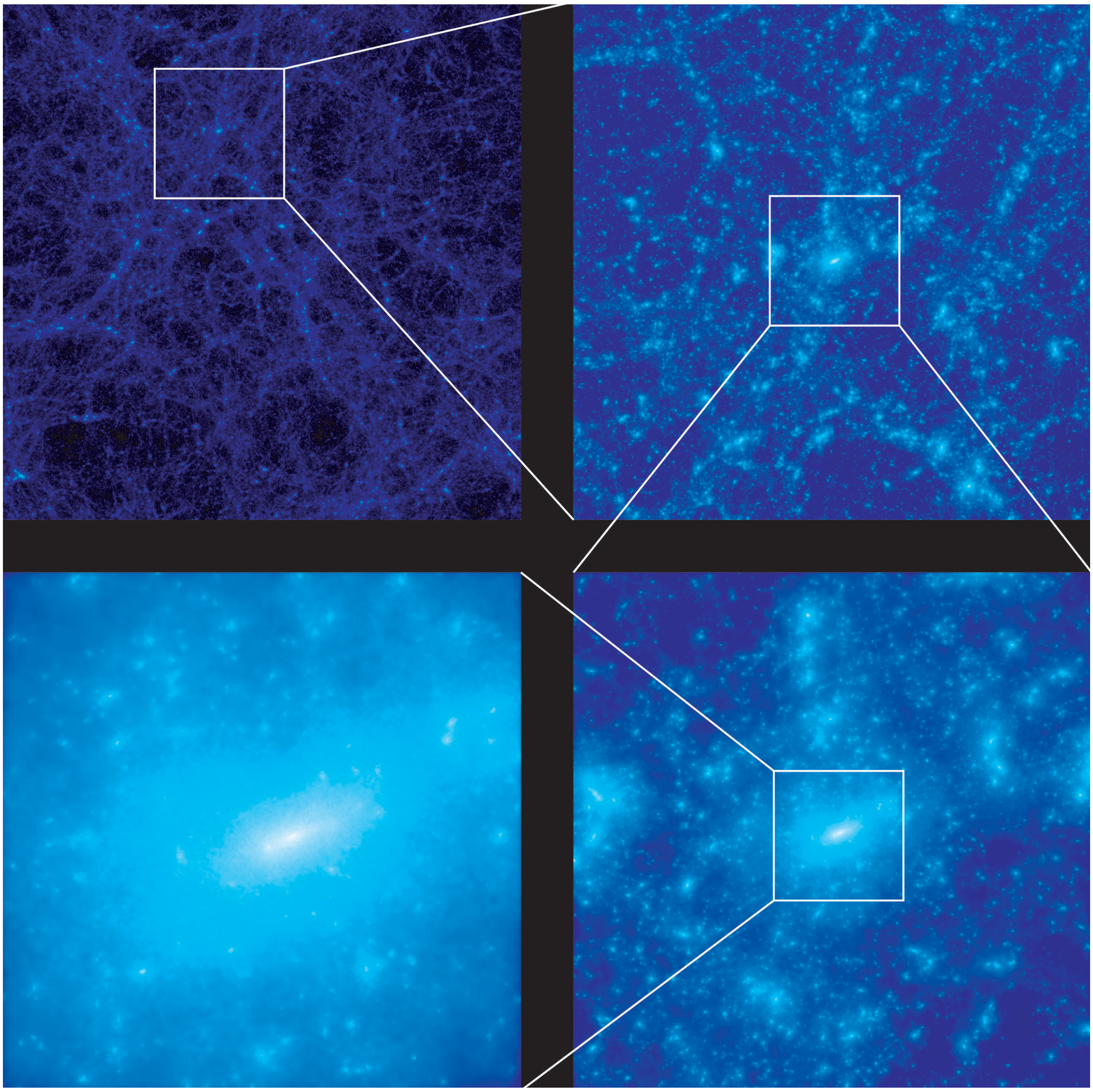

Fig. 2 Snapshot of the cosmological N-body simulation. The upper left panel shows the distribution of particles in the whole simulated region. The box size of the simulation is 100 Mpc, about 326 million light year. Other panels show the magnification of the upper left panel. The magnification level increases in clockwise direction.

al energy E_{th} is E_{th}=0.002, 0.001, and 0.0005 for model A, B, and C, respectively. The mesh size is Δx=Δy=Δz=0.14 r_s when $-10\ r_s < x, y, z < 10\ r_s$ and otherwise gradually increases with x, y, and z. Total number of mesh points is 400^3. We adopted a simulation engine based on the modified Lax-Wendroff scheme with artificial viscosity. In the following, the unit of time is $t_0 = r_s/c$, where c is the speed of light.

Figure 3 shows the density distribution at t=0 and t=3737 for model A. The initial torus deforms itself into an accretion disk by efficiently transporting angular momentum by Maxwell stress. The density distribution is not axisymmetric but shows one-armed spiral density enhancement. The left panel of Fig. 4 shows the time evolution of the ratio of magnetic pressure to gas pressure $1/\beta$ averaged in $2.5\ r_s < R < 15.0\ r_s$, and $-5\ r_s < z < 5\ r_s$. The growth of the magnetic energy saturates when the magnetic energy is about 10% of the thermal energy. The right panel of Fig. 4 shows the time evolution of the ratio of Maxwell stress to pressure, which corresponds to the α parameter of the angular momentum transport in conventional theory of accretion disks. The saturation level of the Maxwell stress decreases in low temperature disks. These numerical results are consistent with the results of lower-resolution global 3D MHD simulations in cylindrical coordinates (Machida *et al.* 2007 in preparation).

4. Three-dimensional Magnetohydrodynamic Simulations of Magnetoconvection

Figure 5 shows the results of magnetohydrodynamic simulation of the solar atmosphere carried out by using the 3D MHD code CANS. We adopted Cartesian coordinates. The number of mesh points is 300^3. The simulation domain includes upper convection zone, photosphere, chromosphere and corona, and its size is 6400 × 6400 × 24000 (km^3). Periodic boundary condition is applied in the horizontal direction. Turbulent convection is driven by cooling at the photospheric layer. A vertical magnetic field is imposed at the initial state.

Shown in the figures are magnetic field lines and the ver-

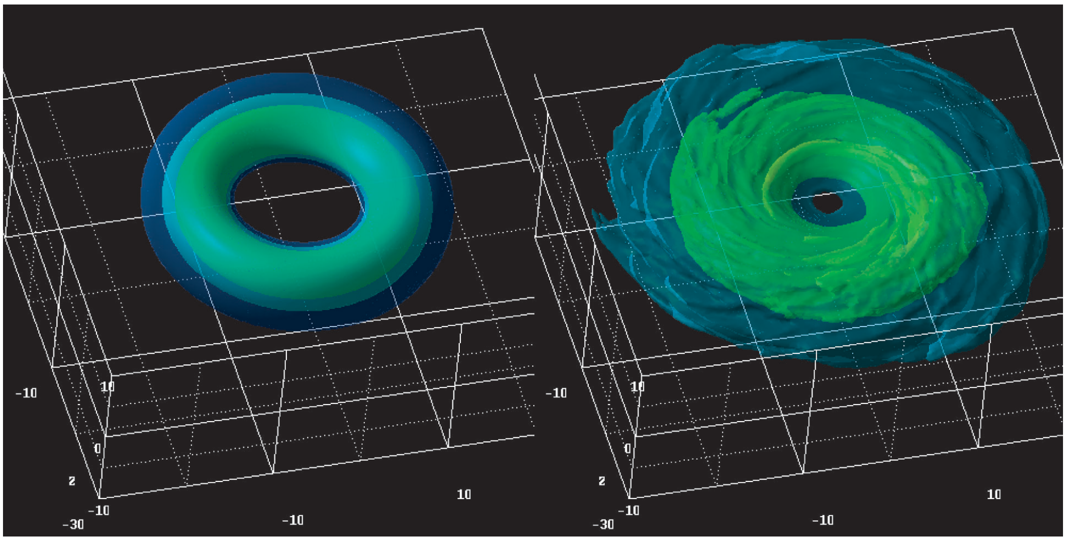

Fig. 3 Initial distribution of density (left panel) and the density isosurfaces at t=3737 (right panel) for model A obtained by global 3D MHD simulations in Cartesian coordinates.

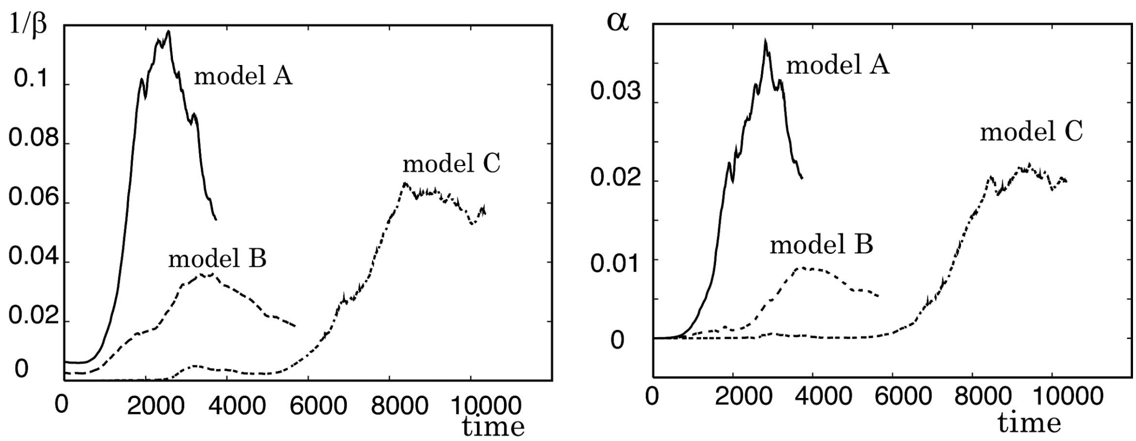

Fig. 4 Time evolution of the average ratio of magnetic pressure to gas pressure (left panel) and Maxwell stress to gas pressure (right panel) for model A, B, and C.

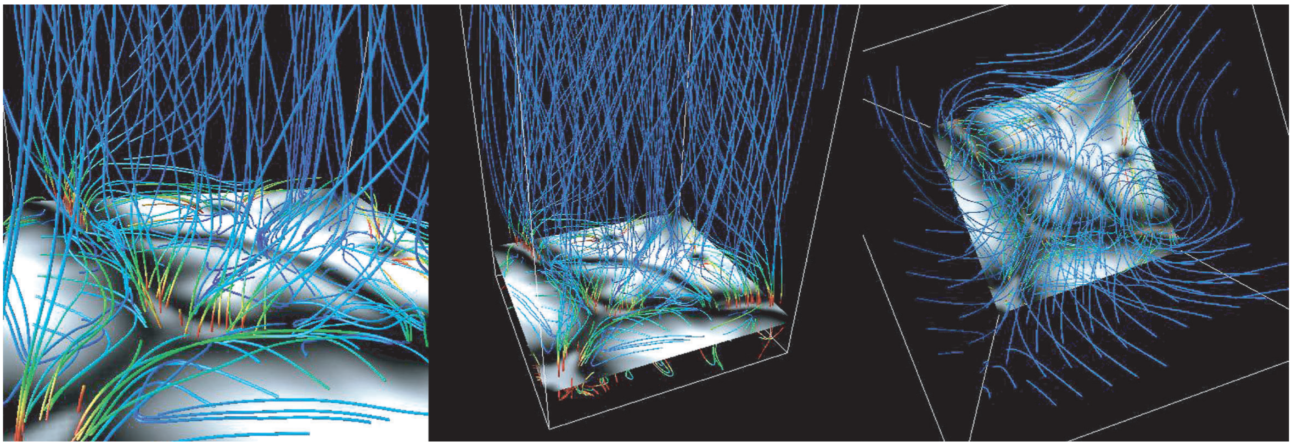

Fig. 5 Numerical results of 3D MHD simulation of magneto-convection in the solar atmosphere. Left panel shows the close-up of the photosphere. Grey scale shows the vertical component of velocity at the photosphere. The light and dark regions show upward and downward flows of convection, respectively. Colored curves show magnetic field lines. Color changes from red to blue as the magnetic field becomes weaker. Middle panel shows the larger region. The right panel is the top view.

tical component of plasma velocity at the photosphere. The latter visualize the convection motion. The color of magnetic field lines corresponds to the field strength; red is strong (about 0.1 T) and blue is weak (about 10^{-3} T). The left panel shows a close-up of photosphere. The light and dark parts show upward and downward flows of convection, respectively. Strong magnetic field is concentrated in the narrow downflow region, which is the well-known feature of photospheric magnetic field.

The middle panel shows a larger field of view of the simulation region. Since the magnetic field is shaken and twisted by convective flows in the photosphere, torsional Alfven waves are created and propagate in the corona. The torsional Alfven wave can be recognized in the top view as the helical field lines (right panel). Such Alfven waves are believed to play an important role in coronal heating and solar wind acceleration.

5. Summary

We have carried out (1) cosmological *N*-body simulation of structure formation in dark-matter dominated universe, (2) three-dimensional global MHD simulations of black hole accretion disks, and (3) three-dimensional MHD simulation of magneto-convection in the solar atmosphere.

Although the time scale covered by simulation (1) is still limited to the early stage of cosmic evolution ($t<3.5$ billion year), clusters of galaxies are already formed. We would like to continue the simulation for time scale of the current age of the universe (t=13.7billion years) and make a numerical catalog of galaxies to statistically compare the numerical results with observations.

For simulations of accretion disks, we are developing a 3D MHD code in cylindrical coordinates which reduces the number of azimuthal mesh points near the rotation axis to avoid short time steps. Longer time scale simulations will be carried out by using such codes.

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References

[1] H.Yahagi and Y. Yoshii, "*N*-body code with adaptive mesh refinement", Astrophys. J., 558, pp.463–475, 2001.

[2] H. Nishikori, M.Machida, and R. Matsumoto, "Global three-dimensional magentohydrodynamic simulations of galactic gaseous disks. I. Amplification of mean magnetic fields in an axisymmetric gravitational potential", Astrophys. J., 641, pp.862–877, 2006.

[3] M. Machida, M.R.Hayashi, and R.Matsumoto, "Global simulations of differentially rotating magnetized disks: Formation of low-β filaments and structured coronae", Astrophys. J., 532, L67–L70, 2000.

[4] R. Matsumoto, and M. Machida, "Sawtooth-like oscillations of black hole accretion disks", proceedings of the IAU Symposium #238, pp.37–42, 2007.

[5] M. Machida, and R. Matsumoto, "Global three-dimensional magnetohydrodynamic simulations of black hole accretion disks: X-ray flares in the plunging region", Astrophys. J. 585, pp.429–442, 2003.

[6] H. Yahagi, "Vectorization and parallelization of adaptive mesh refinement *N*-body code", Publ. Astron. Soc. Japan, 57, pp.779–798, 2005.

宇宙の構造形成とダイナミックス：
宇宙構造形成のN体シミュレーションと磁気流体シミュレーション

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解適合格子（AMR）法に基づくN体シミュレーションコードの地球シミュレータへの実装が完了し、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開始した。宇宙膨張開始後35億年間のシミュレーションの結果、ダークマターハローを伴う銀河団が形成されることが示された。降着円盤グループはカーテシアン座標系3次元の磁気流体コードを用いてブラックホール降着円盤の大局的な3次元磁気流体シミュレーションを行った。その結果、円盤内部の磁気圧がガス圧の10%程度まで増幅されて準定常状態に至るという円筒座標系シミュレーションから得られていた結果が、より解像度の高い計算でも成立することを確認した。また、角運動量輸送率が円盤温度に依存すること、高温円盤では1本腕の渦状構造が形成されることが示された。太陽グループは2006年に打ち上げられた太陽観測衛星「ひので」により可能になった太陽大気の高解像度観測に対応する3次元磁気流体シミュレーションに着手し、太陽コロナの加熱機構、太陽風の加速機構の解明に向けて研究を進めている。

キーワード：宇宙物理学, 銀河形成, 磁気流体力学, 降着円盤, 太陽活動