Cosmic Structure Formation and Dynamics: Magnetohydrodynamic Simulations of Astrophysical Jets and the Implementation of Adoptive Grid *N*-body Code

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By applying magnetohydrodynamic (MHD) codes implemented to the Earth Simulator, we carried out three-dimensional simulations of formation of astrophysical jets. We adopted a Cartesian MHD code to study the stability of magnetically driven jets launched from accretion disks. Numerical results indicate that although the magnetic field lines anchored to the disk are strongly twisted by the rotation of the disk, the jets are not disrupted by the current driven kink instability. The rotation of the jet may be stabilizing the growth of the kink instability. Three-dimensional MHD simulations of the sunspot forming regions of the Sun revealed that jets are produced by the magnetic reconnection between the emerging magnetic loops and the preexisting coronal magnetic fields. We also implemented an adoptive grid *N*-body code to the Earth Simulator to study the formation and evolution of galaxies and cluster of galaxies. We have achieved high vector and parallel performance which enable simulations using 1024^3 particles.

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

1. Introduction

We have implemented simulation codes which incorporate gravitational, magnetic and hydrodynamic interactions and carried out simulations of cosmic structure formation and dynamics. Mori and Umemura [1] implemented a hybrid *N*-body and hydrodynamic code to the Earth Simulator and carried out numerical simulations of galaxy formation based on the bottom up scenario that a galaxy is built up by an assemblage of a numerous sub-galactic clumps. The bubbly structures of gas revealed in their simulation resemble closely the Lyman α emitters recently found in proto-cluster regions. Isobe *et al.* [2][3] carried out high-resolution three-dimensional magnetohydrodynamic (MHD) simulations of the sunspot forming regions of the Sun and revealed that the filamentary structure often observed in such regions arises spontaneously from the magnetic Rayleigh-Taylor instability. The intermittent nature of coronal heating and patchy brightenings in solar flares are naturally explained by the intermittent magnetic reconnection between the emerging filamentary magnetic loops and pre-existing coronal magnetic fields. These achievements clearly demonstrate the potential of the Earth Simulator, which enables us to carry out three-dimensional simulations including multiple levels of the hierarchy in the computational domain.

In the following, we report the results of three-dimensional MHD simulations of formation of astrophysical jets and the implementation of adoptive grid *N*-body code to the Earth simulator.

2. Global Three-dimensional Magnetohydrodynamic Simulations of Jets Launched from Accretion Disks

Collimated outflows of mass and energy (jets) are observed in various astrophysical objects such as active galactic nuclei, microquasars, and in star forming regions. The most energetic bursts in the universe, gamma ray bursts, are also suggested to be related to jets produced during the formation of a black hole. Uchida and Shibata [4], Shibata and Uchida [5] first carried out global MHD simulations of jet formation from accretion disks initially threaded by large-scale magnetic fields. Recently, Kigure and Shibata [6] published the results of global three-dimensional MHD simulations of jet formation by the interaction between an accretion disk and a large-scale magnetic field. They adopted a three-dimensional simulation code based on the CIP-MOCCT scheme [7] in cylindrical coordinates. They showed that non-axisymmetric structures with azimuthal wavenumber $m = 2$ appear in the jet.

Since the magnetic field lines threading the disk are strongly twisted by the rotation of the disk, the jet can subject to the current driven kink instability. In order to study the growth of the kink instability, we prefer three-dimensional MHD code in Cartesian coordinates because it can avoid the singularity at the rotation axis. Figure 1 shows a result of the simulation carried out by using the three-dimensional resistive MHD module in Cartesian coordinates included in the simulation code CANS (Coordinated Astronomical Numerical Software) implemented to the Earth Simulator. Color surfaces show density isosurfaces, and the solid curves denote magnetic field lines.

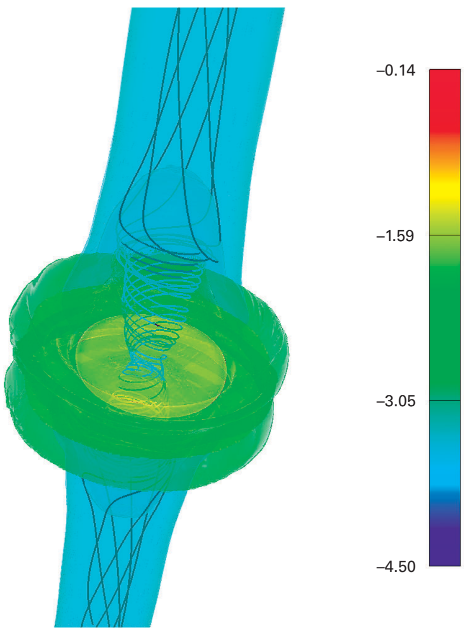

Fig. 1 A result of global three-dimensional MHD simulation of jet formation from accretion disks obtained by using parallelized MHD code CANS in Cartesian coordinates implemented to the Earth Simulator. Colored surfaces show isosurfaces of logarithmic density. Solid curves denote magnetic field lines.

The initial state is a constant angular momentum torus rotating around the central gravitating object. The initial density maximum of the torus is at $r = 10.0$. The ratio of thermal energy and gravitational energy of the torus at this radius is $E_{th} = 0.03$. We assumed isothermal hot corona outside the torus. The initial density of the corona at $r = 10$ is 0.1% of the maximum density of the torus. The simulation region is $-100 < x,y,z < 100$, and the number of mesh points is 400^3. We used non-uniform mesh concentrated near the gravity center at $(x,y,z) = (0,0,0)$. We assumed Newtonian gravity softened in $r < 2.0$. We assumed uniform initial magnetic field parallel to the rotation axis. The plasma β in the corona at $r = 10$ is $\beta = P_{gas}/P_{mag} = 3.0$. We assumed uniform resistivity with magnetic Reynolds number $R_m = 33$. At the initial state, we imposed $m = 1$ non-axisymmetric perturbation for rotation velocity with amplitude 0.1% of the unperturbed rotation speed.

Figure 1 shows that although the magnetic field lines are strongly twisted, the current driven kink instability does not disrupt the jet. Preliminary analysis by Kuwabara *et al.* (2006, in preparation) indicate that the rotation of the jet stabilizes the kink-mode. More detailed analysis will be published in subsequent papers.

3. Three-dimensional Magnetohydrodynamic Simulations of Jets in Sunspot Forming Regions

Studies of solar activities such as flares and coronal mass ejections are one of the essential parts of the space weather predictions since such events are the sources of the disturbances on the electromagnetic fields of the Earth. They can damage orbiting satellites and electric power grids on the ground. Moreover, the studies of them give hints to understand various active phenomena observed in stars, black hole candidates, galaxies, and clusters of galaxies.

Most of the solar activities occur near sunspots, i.e., active

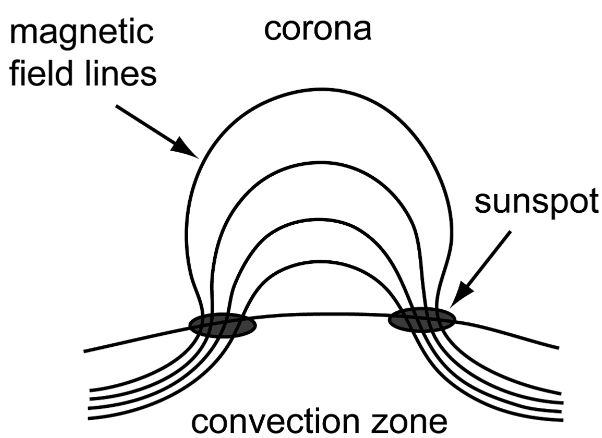

Fig. 2 A schematic picture showing the emerging magnetic loops. Magnetic flux emerges from the convection zone to the corona. The footpoints of magnetic loops correspond to sunspots.

regions, and are closely related to the emergence of magnetic flux from the convection zone to the corona (Figure 2). For example, Hα observations of the chromosphere sometimes show a collimated mass ejection associated with a newly emerging flux (Figure 3; Kurokawa and Kawai [8]). They are thought to be jets along coronal magnetic field lines, and called a surge. Observations by the Yohkoh satellite also revealed that X-ray jets coincide with emerging fluxes (Shibata et al [9]). Furthermore, the association between emerging fluxes and coronal mass ejections is reported (Feynman and Martin [10]). These observations suggest that emerging fluxes and their interaction with the pre-existing magnetic fields are one of the most essential phenomena in terms of the solar activities.

This subject has been studied with numerical simulations. However, in most of the previous works, the initial conditions are very simple and unrealistic due to the limited computational resources. In this study, we performed three-dimensional simulations of the emerging magnetic flux and its interaction with pre-existing coronal magnetic fields with the more realistic initial condition than those of any previous works.

For the simulations, we used the parallelized MHD code CANS implemented to the Earth Simulator. We adopted the CIP-MOCCT scheme with artificial viscosity (Kudoh *et al.* [7]). The simulation box included the convection zone, the cool photosphere/chromosphere and the hot corona. We adopted Cartesian coordinates (x, y, z). The size of the simulation box is -25000 km $< x <$ 25000 km, -25000 km $< y <$ 25000 km, and -2000 km $< z <$ 18000 km. We used 200 × 200 × 200 grid points. In the initial state, we assumed a bipolar coronal field (blue lines in Figure 4a) and a twisted magnetic flux tube imbedded in the convection zone (red lines in Figure 4a). To initiate the evolution, a perturbation was injected in the center of the flux tube. The magnetic field in the corona was assumed to be oblique and anti-parallel to those of the flux tube. We adopted the rigid boundary conditions at the bottom and the periodic boundary conditions in the horizontal direction. The top boundary was treated as the free boundary where waves can be transmitted. In order to simulate magnetic reconnection between the emerging magnetic loops and

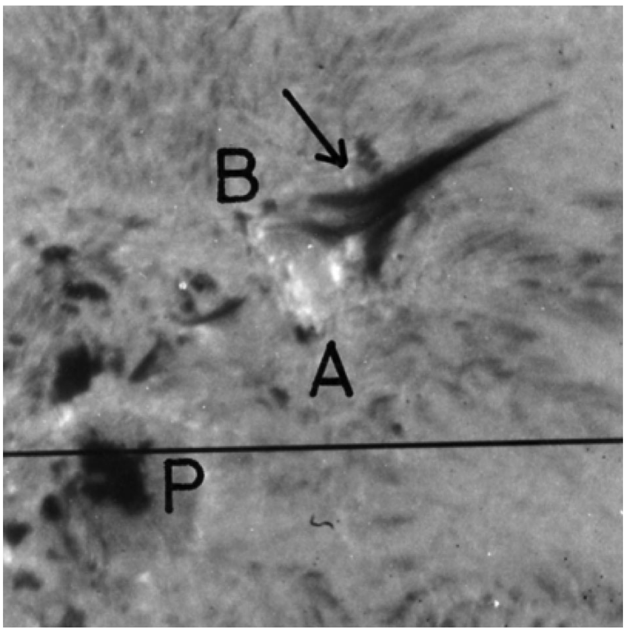

Fig. 3 Observation of a surge taken with the Domeless Solar Telescope at Hida Observatory, Kyoto University. Its observed wavelength is Hα + 0.8 Å. (Kurokawa and Kawai 1993)

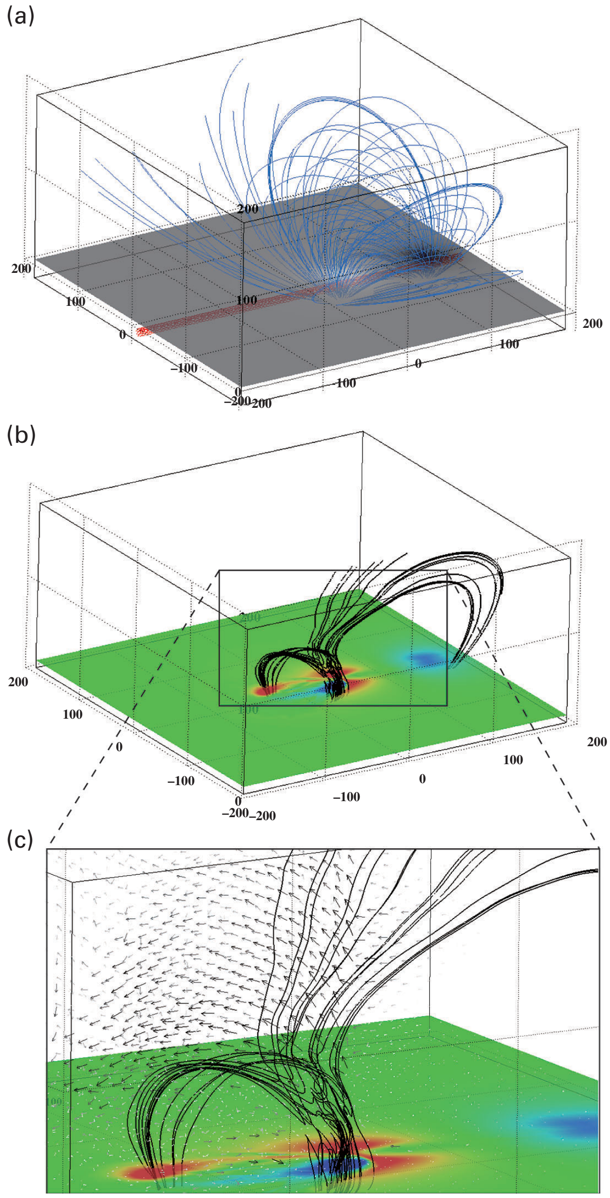

Fig. 4 Results of three-dimensional MHD simulation of jet formation by magnetic reconnection between the emerging magnetic loops and overlying coronal magnetic fields. (a) Initial magnetic field. The blue lines show the bipolar coronal field lines, and the red lines show the twisted magnetic flux tube imbedded in the convection zone. The grey-scales on the horizontal plane indicate the normal magnetic field strengths. (b) Evolved magnetic field. The color on the horizontal plane shows the normal magnetic field strengths and solid lines illustrate the reconnecting magnetic field lines. (c) Zoom-in image of (b). The arrows show the velocity field.

overlying magnetic fields, we assumed the anomalous resistivity which sets in when J/ρ (J is the current density, and ρ is the matter density) exceeds a given threshold.

Figure 4b shows the three-dimensional visualization of the simulation result. The color on the horizontal plane shows the normal magnetic field components and solid lines illustrate the reconnecting magnetic field lines. The Parker instability caused by the initial perturbation drove the rise motion of the flux tube. As the flux tube rose up into the corona, it distorted the coronal magnetic field. A current sheet was formed at the boundary between the newly emerged magnetic loops and the distorted coronal field. As the flux tube came up to the corona, the current density in the sheet continued to increase. Then, the magnetic reconnection took place in the strongest-current part of the currents sheet. Thus generated V-shaped magnetic field lines accelerated the plasma and generated jets (Figure 4c).

4. Implementation of Adoptive-Grid *N*-body Code to the Earth Simulator

Cosmic structures such as galaxies and cluster of galaxies are created by the gravitational attraction of dark matter clumps. Figure 5 shows an example of cosmological *N*-body simulation using 512^3 particles .

We developed a high resolution *N*-body code. The code is based on the Particle-Mesh (PM) method. The PM method itself is a low resolution method, whose resolution is limited by the adopted mesh spacing. However we enhanced the resolution of the PM method introducing the adaptive mesh refinement (AMR) technique which subdivides meshes where higher resolution is required [11].

We vectorized our AMR *N*-body code [12]. Loops which treat only particle data or mesh data are vectorized automatically by the compilers for vector machines. However, loops which simultaneously treat particle data and mesh data are not vectorized automatically. Such loops, which we call "particle-mesh loops", treat particle data which are linked listed from mesh data. If particle-mesh loops are swept along the depth-first order, such loops are not vectorizable. However, if particle-mesh loops are swept along the width-first order, such loops can be vectorized.

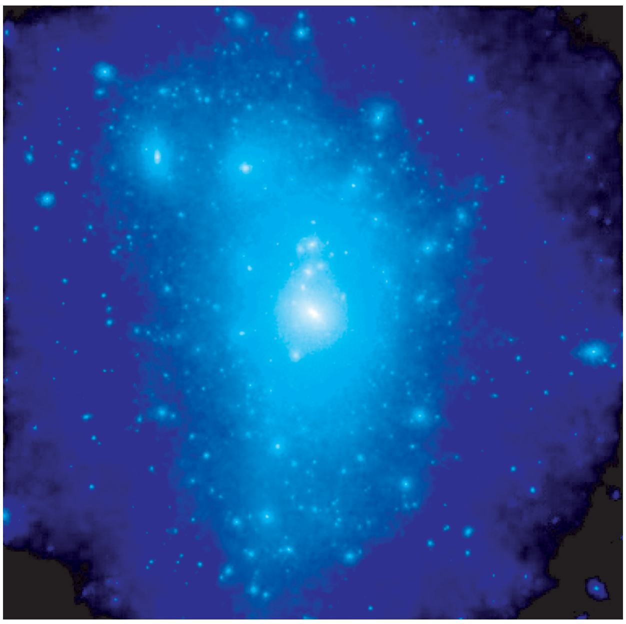

Fig. 5 A result of cosmological *N*-body simulation using 512^3 particles (Yahagi 2002). Colors show the distribution of dark matter particles.

We also parallelized our AMR *N*-body code for distributed memory machines [12]. The decomposition of the particle data and the hierarchical mesh data is nontrivial, while the base mesh decomposition is trivial. First, the hierarchical mesh is sorted by the Morton order. The Morton order is the *N*-shaped recursive order. Then, the hierarchical mesh is decomposed among processes (Figure 6). Since sorting by the Morton order is applied to the hierarchical mesh in each level, cells and their parent cells could be assigned to different processes. Although inter-process communication is required when data is transferred from parent cells to child cells or vice versa, transferred data are bundled naturally, because the hierarchical mesh in each level is sorted by the Morton order, thus the communication is efficient. The particle data decomposition is nontrivial as well as the hierarchical mesh data. We assigned particles to a process to which the finest cell including those particles is assigned (Figure 7). This could cause particle memory imbalance. However, most of main memory is used by the hierarchical mesh data, and the imbalance itself is not so severe.

We developed our vectorized and parallelized AMR *N*-body code on the VPP5000 system installed at the National Astronomical Observatory of Japan. It is not difficult to modify our code to run on the Earth Simulator (ES). Vectorization conditions are almost the same between the ES and the VPP5000 system, and almost all vectorization directives have one-to-one correspondence between the two systems. Moreover, since inter-process communication in our parallel AMR *N*-body code is written in the Message Passing Interface (MPI), our code runs also on the ES without any modifications. However we replaced some *Isend* and *Irecv* pairs by *Sendrecv* in order to tune our code for the ES. As a result, we achieved 99.201% vectorization ratio and 99.9777% parallelization ratio using 128 nodes of the ES. Using this code, we started a 1024^3-particle cosmological *N*-body simulation, which is the largest simulation designed for galaxies statistics, to make a numerical galaxy catalog which enables direct comparison between galaxy formation models and observational data.

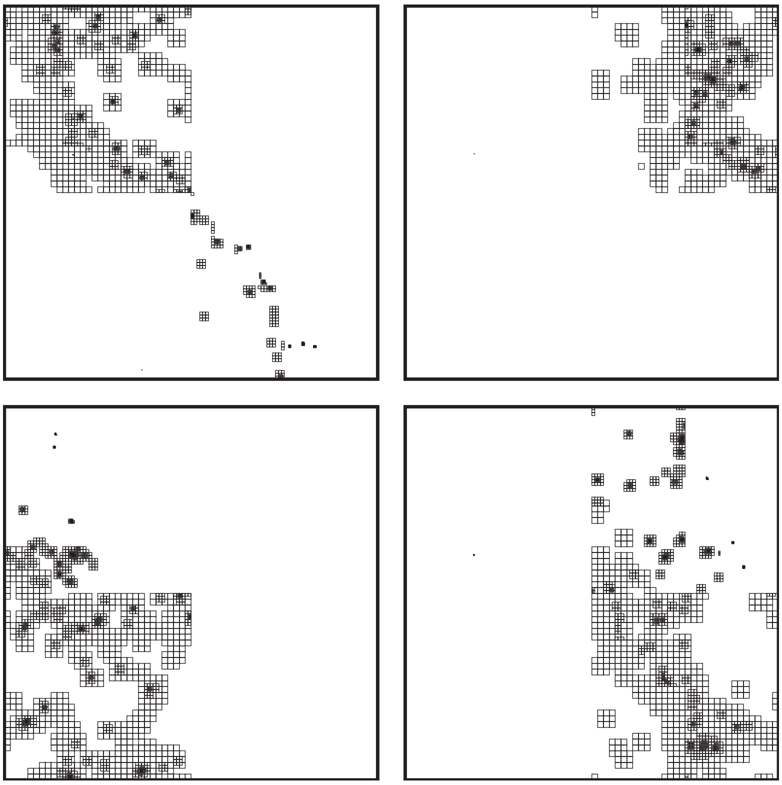

Fig. 6 An example of mesh decomposition. *N*-body simulation of a cosmological constant (Λ) dominated cold dark matter universe (ΛCDM) is carried out. After particles are projected onto a plane, meshes are generated and decomposed among four processes according to the Morton order, the *N*-shaped recursive order.

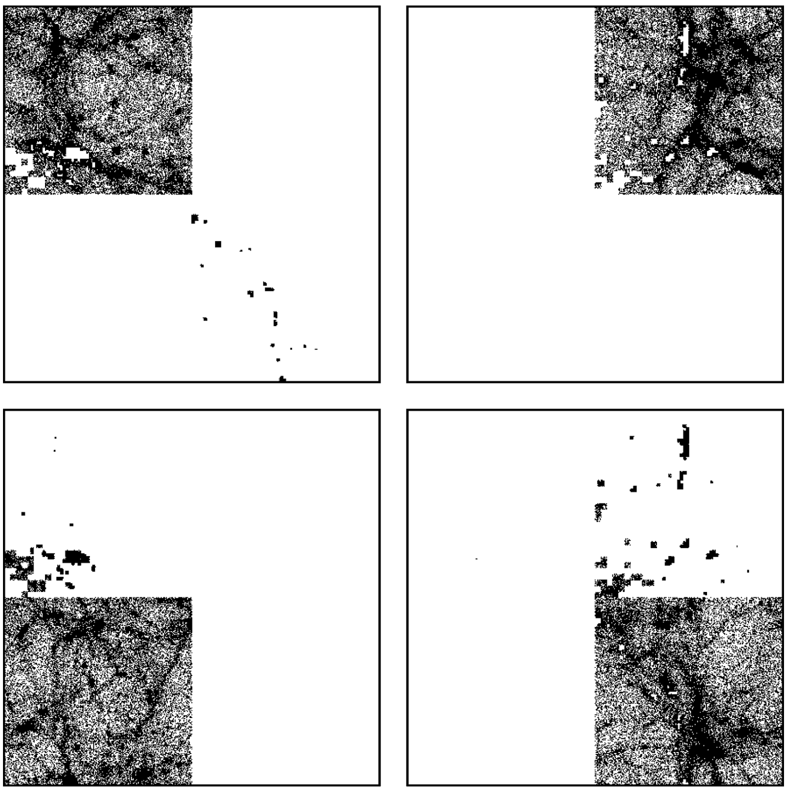

Fig. 7 An example of particle decomposition. After a ΛCDM simulation result is projected onto a plane, particles are decomposed to four processes. Particles are assigned to a process to which the finest cell including those particles is assigned.

5. Summary

We have carried out (1) three-dimensional global MHD simulations of jets launched from accretion disks and (2) three-dimensional MHD simulations of jets in sunspot forming regions. We are also carrying out global three-dimensional MHD simulations of black hole accretion disks initially threaded by toroidal magnetic fields. Preliminary results indicate that accretion disks show sawtooth-like oscillation; when inner torus is created around 10 Schwarzschild radius, non-axisymmetric mode with azimuthal wavenumber $m = 1$ develops, and magnetic fields are amplified inside the torus. When the magnetic energy stored in the inner torus exceeds the threshold, magnetic reconnection takes place and magnetic energy is released. The accumulation and release of magnetic energy repeats quasi-periodically. By using the Earth Simulator, we would like to check the dependence of the numerical results on the grid resolution, and would like to report the results in subsequent papers.

We achieved high vector and parallel performance for the cosmological *N*-body simulation code based on the adoptive-gird scheme. Results of simulations using 1024^3 particles will be reported in near future.

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宇宙の構造形成とダイナミックス：宇宙ジェットの磁気流体シミュレーションと解適合格子N体コードの実装

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地球シミュレータに実装した磁気流体コードを用いて宇宙ジェット形成の3次元シミュレーションを行った。降着円盤から噴出するジェットの安定性をデカルト座標系の3次元シミュレーションコードを用いて調べた結果、円盤の回転により円盤を貫く磁力線は強く捻られるが、ジェットの回転によってキンク不安定性が安定化されていることを示唆する結果が得られた。また、太陽黒点近傍における浮上磁場とコロナ磁場の相互作用をシミュレートし、磁気リコネクションによってジェットが噴出することを示した。次に、銀河・銀河団などの宇宙構造の形成過程をダークマターのダイナミックスを解くことによって調べるため、解適合格子法に基づくN体コードを地球シミュレータに実装した。その結果、高いベクトル・並列効率が得られ、1024^3粒子を用いた世界最大規模のシミュレーションが可能になった。

キーワード：宇宙物理学，磁気流体力学，降着円盤とジェット，太陽活動，銀河形成