Cosmic Structure Formation and Dynamics: Large Scale Numerical Simulations of Solar Activities and Galaxy Formation

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By applying hydrodynamic and magnetohydrodynamic (MHD) codes implemented to the Earth Simulator, we carried out large-scale numerical simulations of cosmic structure formation and dynamics. High resolution three-dimensional MHD simulations of the sunspot forming regions (emerging flux regions) of the Sun 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. We also performed high-resolution three-dimensional numerical simulations of the galaxy formation based on the bottom-up scenario that a galaxy is built up by an assemblage of a numerous sub-galactic clumps. We showed that multiple supernovae in the primordial galaxy can reproduce bubbly structures and luminosity of Lyα blobs recently found in proto-cluster regions. By comparing the numerical results with Subaru observations of the Lyα blobs, we identified the Lyα blobs with primordial galaxies observed in supernovae-dominated phase.

Keywords: Astrophysics, Hydrodynamics, Magnetohydrodynamics, Solar Activities, Galaxy Formation

1. Introduction

We have implemented the parallelized compressible fluid dynamic code AFD2 [1] and the magnetohydrodynamic code CANS [2] to the Earth Simulator and carried out large-scale numerical simulations of cosmic structure formation and dynamics. These codes include gravity, which often plays essential roles in producing the hierarchical structure of the universe. A galaxy, for example, is formed by gravitational attraction of numerous sub-galactic clumps (Figure 1). Stars are formed in the galaxy by gravitational contraction of the interstellar matter. The Sun is such a star confined by its own gravity. Gravity creates stratification of the solar atmosphere consisting of the convection zone, photosphere/chromosphere, and corona. Numerical simulation of the gravitationally stratified atmosphere is computationally challenging because density and characteristic vertical length (scale height) drastically change with height. The Earth Simulator enables us to carry out three-dimensional simulations including multiple levels of the hierarchy (e.g., stars and galaxies, convection zone, photosphere/chromosphere and corona) in the computa-

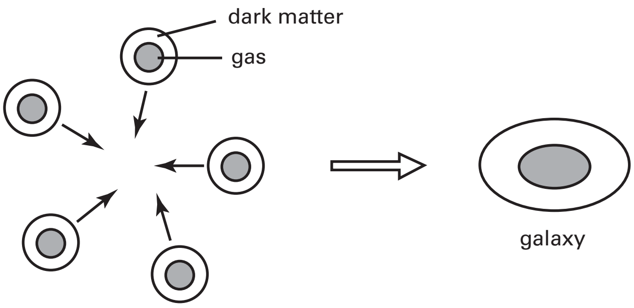

Fig. 1 A Bottom-up scenario of galaxy formation. A galaxy is formed by an assemblage of dark matter clumps. Primordial gas is confined in the gravitational potential of each clump.

tional domain. In the following, we present the results of (1) Large-scale numerical simulations of the sunspot forming regions of the Sun, and (2) High resolution hydrodynamic simulations of galaxy formation.

2. Three-dimensional MHD Simulations of Sunspot Forming Regions

Solar activities such as flares and coronal mass ejections disturb the electromagnetic fields of the Earth and can damage orbiting satellites and electric power grids. Studies of solar activities are essential for the space weather predictions. Moreover, they give hints to understand various active phenomena observed in stars, black hole candidates, galaxies, and cluster of galaxies. Most of the solar activities originate from the emergence of magnetic flux from the convection zone to the corona. The region where the magnetic loops emerge is called emerging flux region. Sunspots are formed at the footpoints of the emerging magnetic loops (Figure 2). Figure 3 shows the Hα image of the emerging flux region taken with the Domeless Solar Telescope at Hida observatory, Kyoto University. Dark filaments connect small sunspots with opposite polarities. The region around the dark filaments is often bright in X-rays. Observations by Yohkoh satellite revealed that X-ray emitting hot plasmas are sometimes ejected in the emerging flux region as X-ray jets [3]. Previous two-dimensional simulations of the interaction of the emerging magnetic loops and overlying coronal magnetic fields successfully reproduced the X-ray jets [4]. However, the origin of the filamentary structure of this region was not resolved.

By using the parallelized MHD code CANS (Coordinated Astronomical Numerical Software) implemented to the Earth Simulator, we performed three-dimensional simulations of the emerging magnetic flux and its interaction with pre-existing coronal magnetic fields. We succeeded to reproduce the filamentary structure observed in the emerging flux region and proposed a new model for the filament formation and coronal heating. These results have been published in Nature [5]. Here we summarize the numerical methods and results of the numerical simulation.

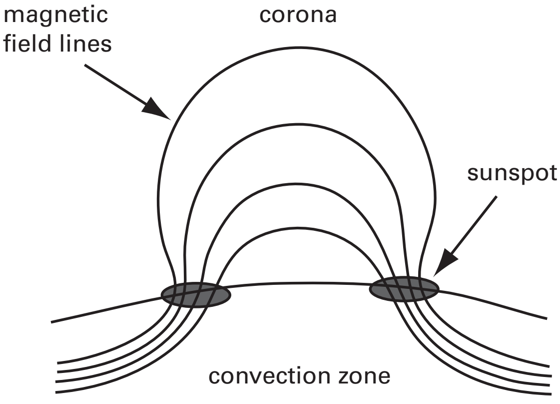

Fig. 2 A schematic picture showing the emerging magnetic loops. Magnetic flux emerges from the convection zone to the corona. The footpoints of magnetic loops correspond to sunspots.

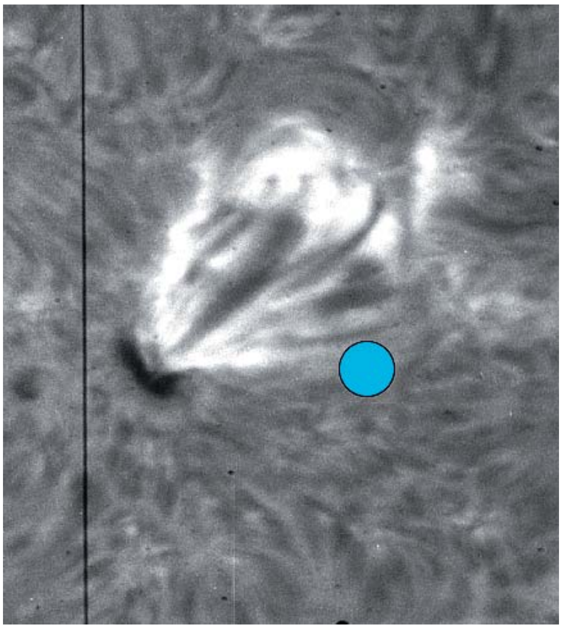

Fig. 3 Hα image of an emerging flux region taken by the Domeless Solar Telescope at Hida Observatory, Kyoto University. The dark filaments connect a sunspot (lower left) and a bright region in the upper right. The blue circle indicates the size of the Earth.

The simulation box includes the convection zone, photosphere/chromosphere and hot corona. We adopted Cartesian coordinates (x, y, z). The size of the simulation box is $0 < x < 48000$ km, $0 < y < 15000$ km, and -1500 km $< z < 19500$ km. We used 800 × 400 × 620 grid points. At the initial state, we assumed a horizontal magnetic flux sheet imbedded in the convection zone. To initiate the time evolution, we perturbed a local domain (22500 km $< x <$ 25500 km) of the flux sheet. The magnetic field in the corona is assumed to be oblique and anti-parallel to those of the flux sheet. We adopted rigid boundary conditions at the bottom and periodic boundary conditions in the horizontal direction. The top boundary is treated as the free boundary where waves can be transmitted. Among the simulation engines implemented to CANS, we adopted the engine based on the modified Lax-Wendroff scheme with artificial viscosity. The simulation code is parallelized by using MPI. In order to simulate magnetic reconnection between the emerging magnetic loops and overlying magnetic fields, we assumed anomalous resistivity which sets in when J/ρ (J is current density, and ρ is matter density) exceeds a threshold.

Figure 4 shows the three-dimensional visualization of the simulation result. The gray surfaces are isosurface of matter density. The color on the slice shows temperature distributions. Blue tubes show magnetic field lines. The semi-circular magnetic field lines near the center of the figure are emerging magnetic loops. They interact with the overlying coronal magnetic fields and create thin current sheets. The current sheet can be identified as the thin high-temperature region along the top of the emerging magnetic loop. Magnetic reconnection taking place in the interacting region creates V-shaped magnetic field lines, which accelerate the hot plasma and create X-ray jets. Density distribution (gray surface) shows narrow filaments around the top of the emerging magnetic loops. These filaments correspond to the arch filament system observed in the Hα image of the emerging flux region (see figure 3). We found that the dense filaments are created due to the magnetic Rayleigh-Taylor instability. The instability grows around the top of the emerging magnetic loops because dense chromospheric matter is lifted against gravity by the magnetic pressure of rising magnetic loops. Such top-heavy density distribution becomes unstable and the heavy cool gas interchanges with the magnetic fields, forming the dense filaments.

The formation of dense filaments due to the magnetic Rayleigh-Taylor instability deforms magnetic field lines and induces small-scale electric currents around the dense filaments. The color in figure 5 shows the distribution of electric current density. Gray surfaces are the density isosurface corresponding to the arch filaments. The gray tubes show magnetic field lines. The dissipation of the filamentary current sheets leads to the heating of the plasma around the dense filaments and creates hot and cool loops existing alternatively. The numerical result naturally explains the coexistence of hot and cold loops indicated by the extreme ultraviolet image of the emerging flux regions. The formation of small-scale current sheets in the emerging flux supports the idea that the corona is heated by dissipation of current sheets. When the filamentary magnetic fields interact with the overlying coronal magnetic fields, magnetic reconnection takes place spatially intermittently. Such 'patchy' reconnection creates fine structures in flares and jets, and should produce patchy brightenings observed in emerging flux regions (see [5] for detail).

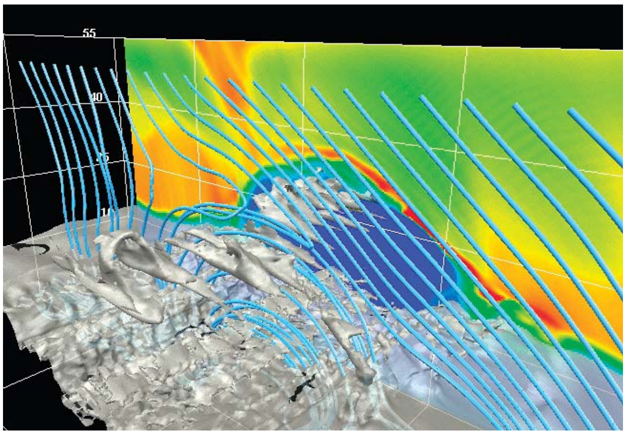

Fig. 4 Three-dimensional visualization of the simulation result. The gray surfaces show the isosurface of density. The color on the slice show the temperature distribution (blue: cold, red: hot). The blue tubes show magnetic field lines.

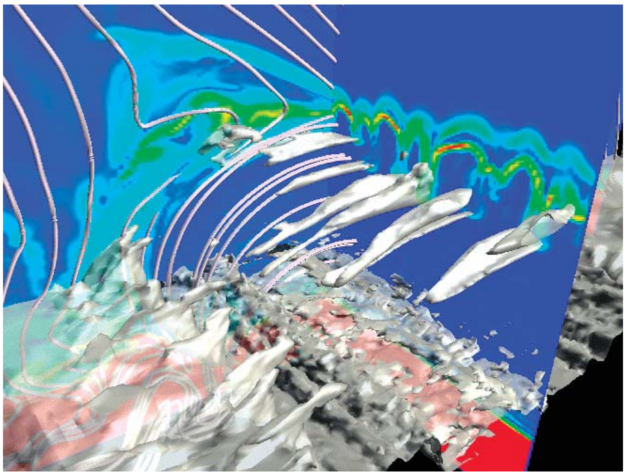

Fig. 5 Color shows the electric current density (red: large, blue: small). The gray surfaces show isosurface of density. Gray tubes show magnetic field lines.

3. Numerical Simulations of Galaxy Formation and Chemical Enrichment of the Inter Galactic Matter

Recent imaging observations of proto-cluster regions by using the Lyα emission line revealed the existence of very luminous and extended Lyα nubulae, so-called Lyα blobs, which have the Lyα luminosity of more than 10^{43} erg/s and physical extent of about 100kpc (1pc = 3.26 light years) [6] [7] [8]. By using the Subaru Telescope, Matsuda et al. (2004) [8] found 35 extended Lyα blobs in the proto-cluster region at redshift z = 3.1. One third of them are apparently not associated with ultraviolet continuum sources that are bright enough to produce Lyα emission. More interestingly, the Lyα blobs have bubbly features. These bubbly structures strongly suggest that the extended Lyα emission in Lyα blobs are produced due to the shock heating by supernova driven galactic outflows. However, it has not been shown whether multiple supernova explosions can actually produce the observed Lyα emission. For this purpose, we carried out high-resolution (1024^3 grids) simulation of galaxy formation including the supernova explosions. Since we already reported the numerical results in the Earth Simulator Journal [9], here we briefly summarize the simulation methods and compare numerical results with Matsuda et al's observation [8]. The full description of this simulation will be published by Mori and Umemura (2005, in preparation).

According to the bottom-up scenario of galaxy formation (figure 1), we model a protogalaxy as an assemblage of 20 dark matter clumps. The total mass of the gaseous matter of the protogalaxy is initially assumed to be 1.3×10^{10}solar mass and the total mass including the dark matter is 10^{11}solar mass. At the initial state, the gas is assumed to be in hydrostatic equilibrium confined by the gravity of the dark matter. Instead of solving the dynamics of each dark matter particle, we represent the gravity of each clump by that of a macro particle and computed the evolution of the macro-particles by solving the gravitational N-body problem. The dynamics of gas components is computed by applying the compressible fluid dynamic code AFD2 based on the AUSM-DV scheme [1]. The parallelization efficiency of the AFD2 code for 1024^3 grid simulations is 55.6% on 128 nodes of the Earth Simulator. Radiative cooling is incorporated using the metalicity-dependent cooling curves by Sutherland and Dopita [10]. Stars are assumed to be formed in Jeans unstable regions. When a star particle is formed, we identify this with approximately 10^4 single stars and distributed the associated mass according to Salpeter's initial mass function. Stars more massive than 8 solar mass explode as type II supernovae and eject their outer layers with synthesized heavy elements.

Figure 6 shows the snapshots of the gas density, the gas metalicity, and the gas temperature distribution in a slice along the X-Y plane. The gas temperature increases up to about 10^8K and expanding hot bubbles of kpc size are produced. They are enclosed by cold, dense shells. The supernovae-driven shock waves quickly collide with each other and generate super-bubbles with 10kpc size. At around 200Myr, individual bubbles have merged into an expanding super-bubble. The interactions of expanding hot bubbles give rise to a complex structure in the inner regions, where a metal-rich gas coexists with an almost primordial gas. The rightmost panels of figure 6 show that the simulation box is filled with warm, chemically enriched gas. The out-flowing gas escapes from the gravitational potential of the whole system and is ejected into the intergalactic space.

Finally let us compare the numerical results with observation of Lyα blobs. The left panels of figure 7 show the Lyα image of two of the Lyα blobs reported by Matsuda et al. [8]. Size of the Lyα emitting clouds are larger than 100kpc, thus they are much larger than current galaxies. The right panels of figure 7 show the 'virtual' image of the Lyα blobs obtained by assuming optically thin gas in collisional ionization equilibrium and using the MAPPINGSIII code by Sutherland and Dopita [10]. We found that the Lyα luminosity can account for the observed luminosity of Lyα blobs. The bubbly structures created by multiple supernovae explosions are quite similar to the observed features of Lyα blobs.

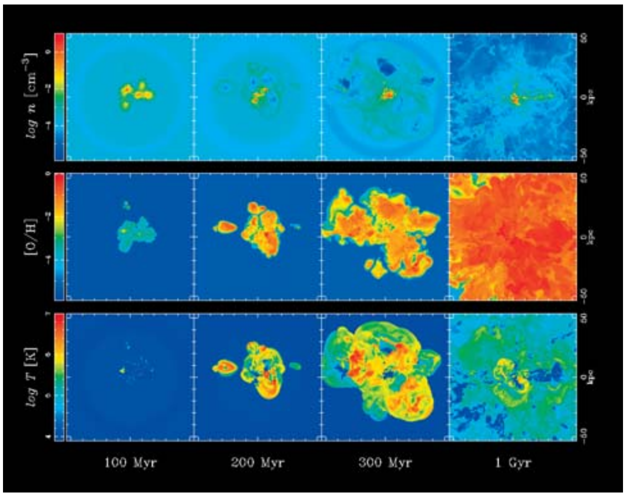

Fig. 6 Snapshots of the gas density, metalicity, and temperature distribution in a slice along the X-Y plane.

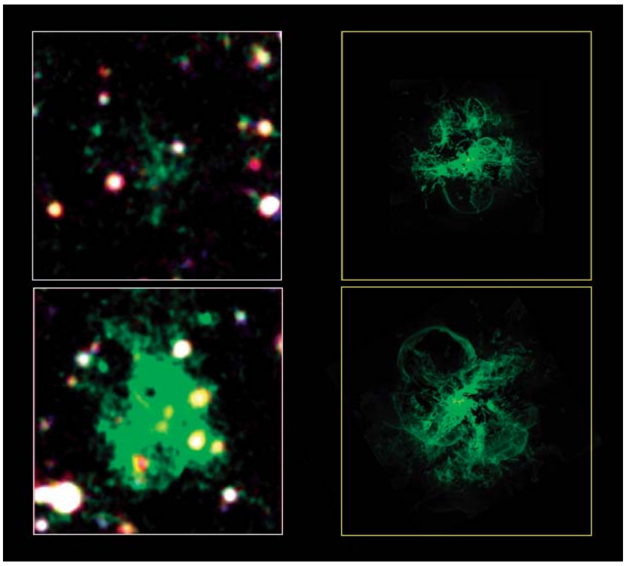

Fig. 7 (Left) Lyα images of the Lyα blobs observed by Matsuda et al. (2004) using the Subaru Telescope [8]. (Right) Projected distribution of the Lyα emission derived from numerical results.

4. Summary

We have carried out (1) three-dimensional MHD simulations of the emerging magnetic loops in sunspot forming regions, and (2) three-dimensional fluid dynamic simulations of the galaxy formation based on the bottom-up scenario of galaxy formation. In the former simulation, we found that arch filaments observed in the emerging flux regions are spontaneously created by the magnetic Rayleigh-Taylor instability. Numerical results also indicated that filamentary distribution of electric currents produce spatially intermittent heating and patchy brightenings. The simulation of the galaxy formation indicated that the distribution of the Lyα emission derived by numerical results is similar to the image of the Lyα blobs in proto-cluster regions recently observed by the Subaru telescope. We also found that the inhomogeneous mixing of heavy elements produces a large spread of metalicities. We conclude that the Lyα blobs can be identified with primordial galaxies observed in a supernovae-dominated phase. In the simulation we presented in this report, heavy elements are blown out of the outer boundary of the simulation box. In order to study how far from the production sites can heavy elements be ejected, the simulation box should be much larger than the current simulation. In order to carry out such simulations, keeping the resolution in the central region of the proto-galaxy, we have implemented a parallel nested grid code AFD4 to the Earth Simulator. We would like to report the results of simulations using AFD4 in near future.

Bibliographies

1) M. Mori, A. Ferrara, and P. Madau, 2002, "Early metal enrichment by pregalactic outflows, II. Three-dimensional simulations of blow-away", Astrophys. J., 571, pp.40-55
2) http://www.astro.phys.s.chiba-u.ac.jp/netlab/astro/
3) K. Shibata et al., 1992, "Observations of X-ray jets with the YOHKOH soft X-ray telescope", Publ. Astron. Soc. Japan, 44, L173-L179
4) T. Yokoyama, and K. Shibata, 1995, "Magnetic reconnection as the origin of X-ray jets and H-alpha surges in the Sun", Nature 375, pp. 42-44
5) H. Isobe, T. Miyagoshi, K. Shibata and T. Yokoyama, 2005, "Filamentary structure on the Sun from the magnetic Rayleigh-Taylor instability", Nature, 434, pp.478-481
6) C.C. Steidel, K.L. Adelberger, A.E. Shapley, M. Pettini, M. Dickinson, and M. Giavalisco, 2000, "Lyα imaging of a proto-cluster region at $<z> = 3.09$", Astrophys. J., 532, pp.170-182
7) Y. Ohyama, Y. Taniguchi, K.S. Kawabata, Y. Shioya, T. Maruyama, T. Nagao, T. Takata, M. Iye, and M. Yoshida, 2003, "On the origin of Lyα blobs at high redshift: kinematic evidence of a hyperwind galaxy at $z = 3.1$", Astrophys. J., 591, L9-L12
8) Y. Matsuda et al., 2004, "A Subaru search for Lyα blobs in and around the protocluster region at redshift $z = 3.1$", Astrophys. J., 128, pp.569-584
9) R. Matsumoto, M. Mori and M. Umemura, 2005, "Large scale numerical simulations of galaxy formation", Journal of the Earth Simulator, 2, pp.34-40
10) R.S. Sutherland and M.A. Dopita, 1993, "Cooling functions for low-density astrophysical plasmas", Astrophys. J. Supplement, 88, pp.253-327

宇宙の構造形成とダイナミックス：
太陽活動と銀河形成の大規模数値シミュレーション

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地球シミュレータに実装した流体及び磁気流体コードを適用することにより、宇宙の構造形成とダイナミックスの大規模数値シミュレーションを実施した。第一の成果は、太陽黒点形成領域（浮上磁場領域）の高分解能3次元磁気流体シミュレーション結果に基づき、浮上磁場領域で観測されるアーチフィラメントが磁気レイリーテイラー不安定性によって自発的に形成されることを明らかにしたことである。非一様なコロナ加熱や太陽フレアにおけるパッチ状の増光などはフィラメント状に上昇する磁気ループとコロナ磁場の間の磁気リコネクションによって自然に説明することができる。この成果はNature誌に発表された。第二の成果はサブクランプの合体によって銀河が形成されるというボトムアップシナリオに基づく銀河形成の高分解能3次元シミュレーションを行い、すばる望遠鏡によって銀河団形成領域に多数発見された巨大なライマンα輝線雲が形成途上にある銀河であることを明らかにしたことである。原始銀河で多数発生する超新星爆発の効果を含めたシミュレーションの結果、観測されたライマンα輝線雲の光度、バブル状構造などを再現することができた。

キーワード：宇宙物理学，流体力学，磁気流体力学，太陽活動，銀河形成