Cosmic Structure Formation and Dynamics: Numerical Simulations Linking the Hierarchical Structure of the Universe

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By implementing hydrodynamical and magnetohydrodynamical codes to the Earth Simulator, we carried out numerical simulations of cosmic structure formation and dynamics including interactions between sub-systems and the whole system. We present the results of high-resolution (1024^3 grid) hydrodynamical simulations of the formation of a galaxy based on the bottom-up scenario, in which a galaxy is built up by an assemblage of a numerous sub-galactic systems. We showed that heavy elements ejected by supernova explosions chemically enrich the forming massive galaxy. In addition to the hydrodynamical coupling, magnetic processes can link-up the hierarchical structures of the universe. Prototypes of such magnetic interactions can be found in solar atmospheres. We carried out three-dimensional magnetohydrodynamic simulations of magnetic energy transport from the solar convection zone to the corona. When an emerging twisted flux tube interacts with overlying coronal magnetic fields, strong twist is injected into the open coronal fields by magnetic reconnection. As a result of this process, shear Alfven waves propagate upward. This mechanism could cause coronal jets and coronal mass ejections. Finally, we briefly discuss prospects for future simulations.

Keywords: Astrophysics, Hydrodynamics, Magnetohydrodynamics, Galaxy Formation, Hierarchical Structure

1. Introduction

The universe has hierarchical structure consisting of stars, galaxies, and cluster of galaxies (Figure 1). In this hierarchical system, local sub-systems (e.g., supernova explosions) can affect the structure and evolution of the whole system (e.g., a galaxy). The left panel of figure 1 shows a result of the N-body simulation using 512^3 particles of the evolution of the dark matter distribution in the expanding universe (Yahagi 2002). The gravitationally interacting dark matters form large-scale structure of the universe. The gas trapped in the gravitational potential of dark matter clumps forms galaxies consisting of stars and the interstellar gas (mid panel of figure 1). The interstellar gas is recycled by supernova explosions (right panel of figure 1). Previously, due to the limitation of computational capabilities, each level of the hierarchy had been simulated separately. The Earth Simulator enables us to carry out global simulations including multiple levels of the hierarchy in the computational domain.

The purpose of this project is to develop numerical schemes to link up the hierarchical structure by incorporating hydrodynamic, magnetic and radiative interactions. In 2003, we implemented hydrodynamical and magnetohydrodynamical codes to the Earth Simulator and carried out simulations of the galaxy formation and the magnetic coupling between the solar convection zone and the corona.

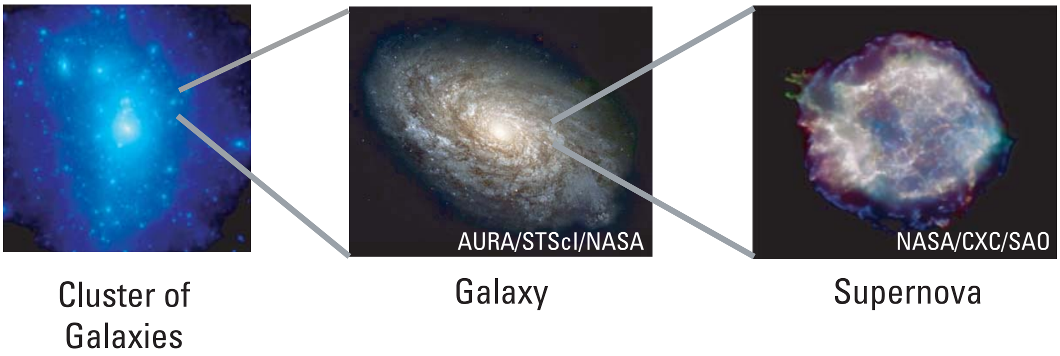

Fig. 1 Hierarchical structure of the universe. The left panel shows the result of N-body simulations of the formation of dark matter cluster (Yahagi 2002). The middle panel shows the Hubble Space Telescope image of a spiral galaxy NGC4414. The right panel shows the Chandra X-ray image of the supernova remnant Cas A.

2. Implementation of Simulation Codes

We implemented the following codes to the Earth Simulator. (1) AFD2: Compressible fluid dynamic code based on the finite volume (AUSMDV+MUSCL) method (Mori, Ferrara and Madau 2002). The dark matters are treated as gravitationally interacting particles. (2) CANS: Integrated magnetohydrodynamic (MHD) code for astrophysical numerical simulations developed by the ACT-JST project (2000–2002, P.I. R. Matsumoto, mainly coded by T. Yokoyama). The simulation engine can be chosen from modified Lax-Wendroff scheme, Roe-TVD scheme, and CIP-MOCCT scheme. (3) ARPS: Astrophysical rotating plasma simulator designed for global three-dimensional MHD simulations of accretion disks (mainly coded by R. Matsumoto). These codes have been parallelized by using MPI. The parallelization ratio of these codes is more than 99.9%. The parallelization efficiency of AFD2 for 1024^3 grid simulations is 55.6% on 128 nodes of the Earth Simulator. For CANS and ARPS, the parallelization efficiency exceeds 50% for 64 nodes.

3. Hydrodynamical Simulations of Galaxy Formation

Our understanding of galaxy formation has greatly deepened in last decade due to multi-wavelength observations of star-forming galaxies at high redshifts. Optical observations have revealed the presence of a number of Lyman break galaxies (LBGs) at redshifts of $3 < z < 5$. Since LBGs are quite young, they could hold information on the early chemical enrichment of galaxies.The theoretical models of galactic chemical evolution have often assumed the homogeneous ISM, with the instantaneous and perfect mixing of heavy elements synthesized in supernovae (SNe). However, the energy input and metal ejection by SNe are likely to proceed in an inhomogeneous fashion. Thus, simulations that can resolve SN remnants are required to properly model the chemical evolution of primordial galaxies. We performed high resolution hydrodynamic simulations of a very large burst of multiple SNe in a forming galaxy.

According to the general concept of hierarchical scenarios of galaxy formation we build up the galaxy as an assemblage of a large number of sub-galactic structures. The galaxy as a whole is set to be a system with a random distribution of condensations in a radius of 71 kpc. The small condensations have a mass $2 \times 10^9 M_\odot$ within a radius 5.8 kpc.The gas dynamics is pursued by a three-dimensional hydrodynamic scheme with 1024^3 Cartesian grids. The simulation box has a (physical) size of 142 kpc and the spatial resolution is 137 pc. Radiative cooling losses are calculated self-consistently using the metalicity-dependent cooling function. The set of basic equations are numerically solved by a parallel version of the AFD2 scheme. Stars are formed in regions where the criterion of star formation is satisfied. We assume that the star formation rate (SFR) is proportional to the local gas density and inversely proportional to the local dynamical time. A star more massive than 8 $M_\odot$ is assumed, after the main sequence lifetime, to undergo a Type II SN explosion, releasing a total energy of 10^{51}erg and expel synthesized heavy elements.

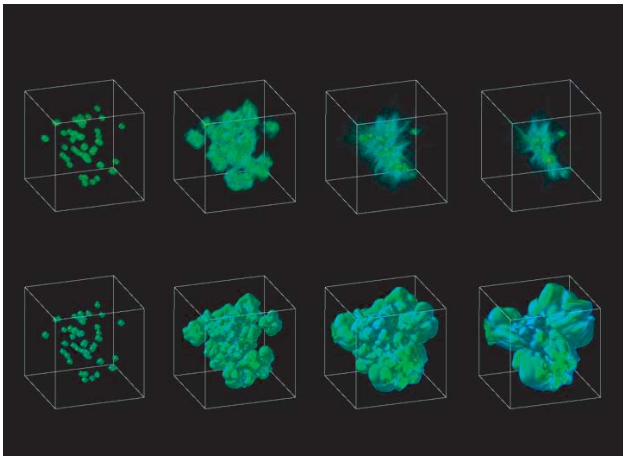

Fig. 2 Results of numerical simulation of galaxy formation. Snapshots for the distribution of density (upper panels) and metalicity (lower panels) at the different elapsed times (0.01, 0.4, 0.8, and 1.2 Gyr from left).

Figure 2 shows the snapshots for the distribution of density (upper panels) and metalicity (lower panels) as a function of elapsed time from 0.5×10^7 to 10^9 yr. Owing to the efficient radiative cooling, the gas temperature rapidly drops, which induces a dynamical contraction of gas in each clump. The density in the central region of each clump increases by the accretion of the surrounding gas, and eventually the intensive star formation is triggered. When massive stars begin to explode as SNe II, the gas in the vicinity of the supernova acquires the thermal energy and synthesized heavy elements are released from SNe II. Then, the gas temperature locally increases up to about 10^8K, and expanding hot bubbles of several kpc are produced; they are enclosed by cooled, dense shells. Subsequent SN explosions further accelerate the expansion of hot bubbles and the ambient gas is continuously swept up by the shells.

The gas in the vicinity of SNe is polluted with synthesized heavy elements ejected from SNe, but a large amount of the gas still retains low metalicity. 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. They are separated from each other by cool shells. Since a part of gas in the outer region has a velocity higher than the escape velocity of this galaxy, it might escape from the galactic potential well. These winds are an efficient mechanism to distribute the heavy elements over cosmological volumes.

4. Magnetohydrodynamical Simulations Connecting the Solar Convection Zone and Corona

Solar flares and coronal mass ejections are essential factor of solar-terrestrial environment. Therefore understanding the basic physics of them is important from the viewpoint of space weather problem. As a first step for the self-consistent modeling of solar flares and coronal mass ejections, we carried out three-dimensional MHD simulation of emerging flux and its interaction with pre-existing magnetic fields in the corona.

The simulation domain includes the upper convection zone, photosphere, chromosphere and corona, which is resolved by at most $500 \times 500 \times 800$ grid points. The basic equations are three dimensional magnetohydrodynamic equations. The magnetic field initially located in the convection zone rises through the photosphere into the upper atmosphere by so called Parker instability (undular mode of magnetic buoyancy instability). If there is pre-existing magnetic field in the corona, magnetic reconnection can occur between the emerging magnetic field and the coronal field.

Figure 3 shows a snap shot of magnetic field lines (black solid lines), velocity field (arrows), and density distribution (color) for a model starting from the magnetic flux sheet imbedded in the convection zone. The omega-shaped field lines are characteristics of emerging magnetic field due to the Parker instability (Shibata et al. 1989). In this calculation an anomalous resistivity model is assumed, in which the resistivity is enhanced where electric current is strong. This results in localized resistivity, and hence Petschek type fast reconnection occurs. It is found that strong current sheet is formed between the emerging magnetic field and pre-existing coronal field. Fast reconnection occurs between them. The vicinity of the reconnection region (red square) is shown in the smaller panel. It shows the magnetic field lines (purple solid lines), velocity field (arrows) and gas pressure distribution (color). The discontinuity of pressure near the reconnection region is a standing shock wave of MHD slow mode, which is a characteristic of Petschek type fast reconnection.

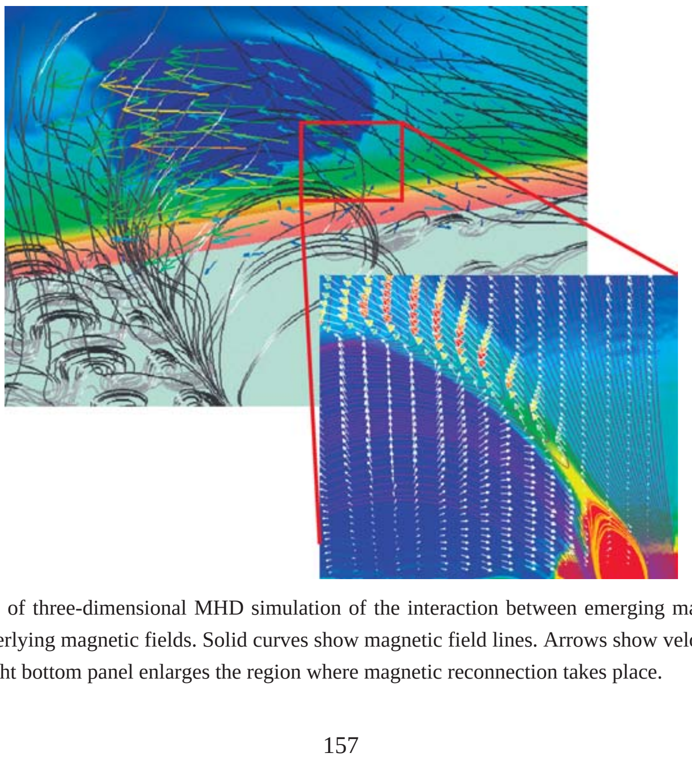

Fig. 3 Results of three-dimensional MHD simulation of the interaction between emerging magnetic loops and overlying magnetic fields. Solid curves show magnetic field lines. Arrows show velocity vectors. The right bottom panel enlarges the region where magnetic reconnection takes place.

Figure 4a shows a side view of magnetic fields for a model starting from a twisted flux tube imbedded in the convection zone. The purple tubes show emerging magnetic flux tube, and the blue tubes show the coronal magnetic fields. Twisted flux tube forms omega-shaped loops, and the loop expands by its magnetic pressure. Magnetic reconnection occurs between twisted emerging flux and coronal fields. Figure 4b shows the top-side view near the emerging loop top. The region under the photosphere is masked. Strong twist is injected into the open coronal fields by magnetic reconnection, and the shear Alfven wave propagates upward as a result of this process. This wave propagation could cause coronal jets and coronal mass ejections.

5. Summary

We have carried out numerical simulations of (1) the formation of a galaxy through an assemblage of sub-galactic structures, and (2) the emergence of solar magnetic loops through the convection zone into the corona. In the former simulation, hydrodynamical processes link the sub-system (e.g., Supernova) to the whole system. (e.g., a galaxy). In the latter model, magnetic fields connect different layers of the solar atmosphere. (convection zone and the corona). Magnetic reconnection taking place in a localized region also affects the global structure of magnetic fields. In order to simulate local sub-systems with higher spatial and temporal resolution, we are going to implement parallelized nested-grid schemes and Adaptive Mesh Refinement (AMR) schemes. Radiative coupling between different layers will also be studied by implementing radiation hydrodynamics/magnetohydrodynamics codes.

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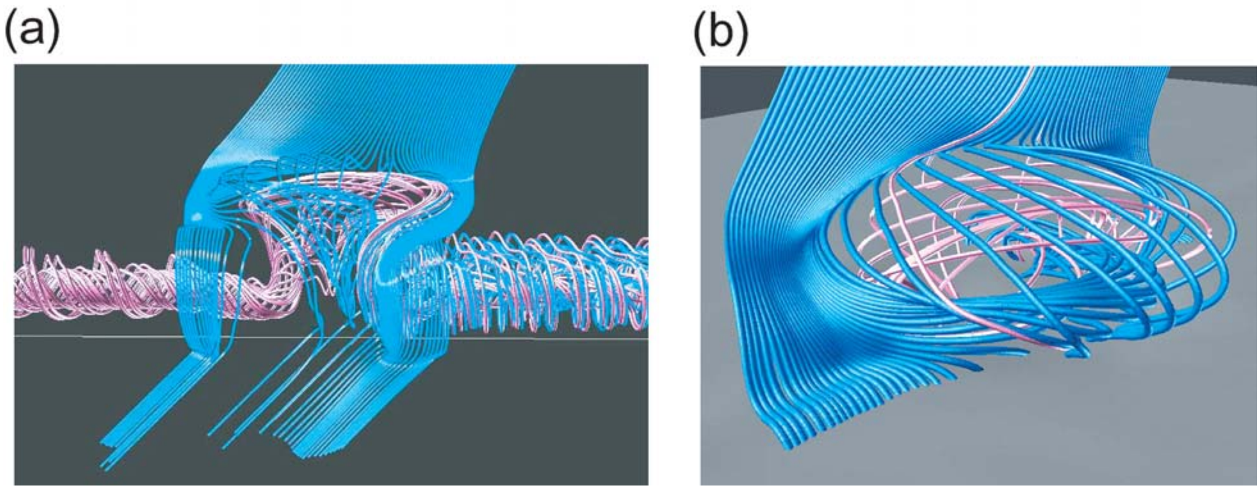

Fig. 4 (a) Side view of the emerging twisted magnetic flux tube interacting with overlying coronal magnetic fields. (b) Top view of the magnetic field lines. Purple tubes show magnetic field lines of the emerging magnetic loop. Blue tubes show coronal magnetic fields.