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Magnetohydrodynamic Simulation of Emerging Flux Region of the Sun

Hiroaki Isobe[1]*, Takehiro Miyagoshi[2], Kazunari Shibata[3],
Takaaki Yokoyama[1], and Ryoji Matsumoto[4]

[1] *Department of Earth and Planetary Science, University of Tokyo, Bunkyo-ku, Hongo, Tokyo 113-0033, Japan*
[2] *Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan*
[3] *Kwasan and Hida Observatories, Kyoto University, Yamashina, Kyoto 607-8471, Japan*
[4] *Department of Physics, Faculty of Science, Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan*

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Abstract We present the result of magnetohydrodynamic simulations of magnetic flux emergence in the solar atmosphere. Magnetic flux emergence is the origin of sunspots and active regions, and often associated with solar flares and coronal mass ejections. Owing to the high-resolution achieved by the Earth Simulator, we could simulate the formation of turbulent, fine structures in the emerging flux region as a result of global dynamics. Our simulation results naturally explain many observed features such as arch filament system and intermittent coronal heating.

Keywords: Solar physics, magnetohydrodynamics, coronal heating, emerging flux, magnetic reconnection

1. Introduction

The outer atmosphere of the Sun, namely the chromosphere and the corona, is hotter than its visible surface and permeated with magnetic field. Observations from ground based telescopes and spacecrafts have revealed that the solar atmosphere is full of explosive, energetic events such as flares, jets and coronal mass ejections, all being due to sudden release of magnetic energy. These explosive events have significant influence on the space environment around the Earth and human activities [1, 2]. Furthermore, recent astronomical observations have discovered similar magnetic activities in various astronomical bodies such as stars, galaxies and accretion disks [3]. Thus there are increasing demands, both practically and academically, for better understanding of magnetic activities in the Sun. Numerical simulation is a powerful tool for studying these phenomena, because they are intrinsically time-dependent and non-linear.

In this paper we present the results of three-dimensional magnetohydrodynamic simulations of an emerging flux region (EFR) of the Sun. EFR is where a new magnetic flux bundle emerges through the photosphere (the visible surface of the Sun) in to the upper atmosphere. The ultimate origin of the solar magnetic field is the dynamo action in the solar interior. Though the dynamo process is still poorly understood, it is believed that the large scale magnetic flux is generated near the bottom of the convection zone, and then the generated magnetic flux rises through the convection zone by magnetic buoyancy and eventually emerge through the photosphere [4]. A schematic illustration of EFR is shown in Figure 1. The characteristic feature of EFR in the atmosphere is the Ω-shaped loops (i.e., magnetic field lines whose shape is similar to the capital Greek character Omega) created by the Parker instability (undular mode of the magnetic buoyancy instability) [4, 5].

Emerging fluxes are the key ingredient of solar magnetic activities. They are the origin of sunspots and active regions. They interact with pre-existing magnetic field in the corona and produce small flares and jets [6, 7]. They also play important role in triggering coronal mass ejections [8, 9]. Deep understanding of physical processes in EFRs is therefore essentially important in the study of solar activities and the space weather.

One of the puzzling issues related to EFR is the origin of its fine structures. In Fig. 2 we show examples of high-resolution observations of EFRs. The upper panel shows an EFR on the solar disk observed in H-alpha line of the Hydrogen atom, taken by the Domeless Solar Telescope

* ***Corresponding author***: *Hiroaki Isobe, Department of Earth and Planetary Science, University of Tokyo, Bunkyo-ku, Hongo, Tokyo 113-0033, Japan, E-mail: isobe@eps.s.u-tokyo.ac.jp*

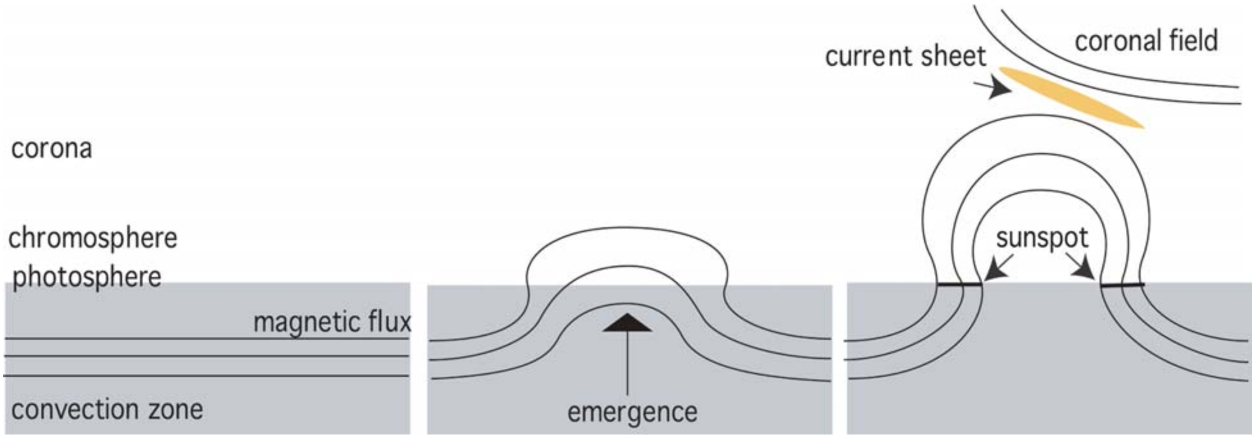

Fig. 1 Schematic illustration of an emerging flux region. The solid lines represent magnetic field lines, and the shaded area corresponds to below the visible surface of the Sun.

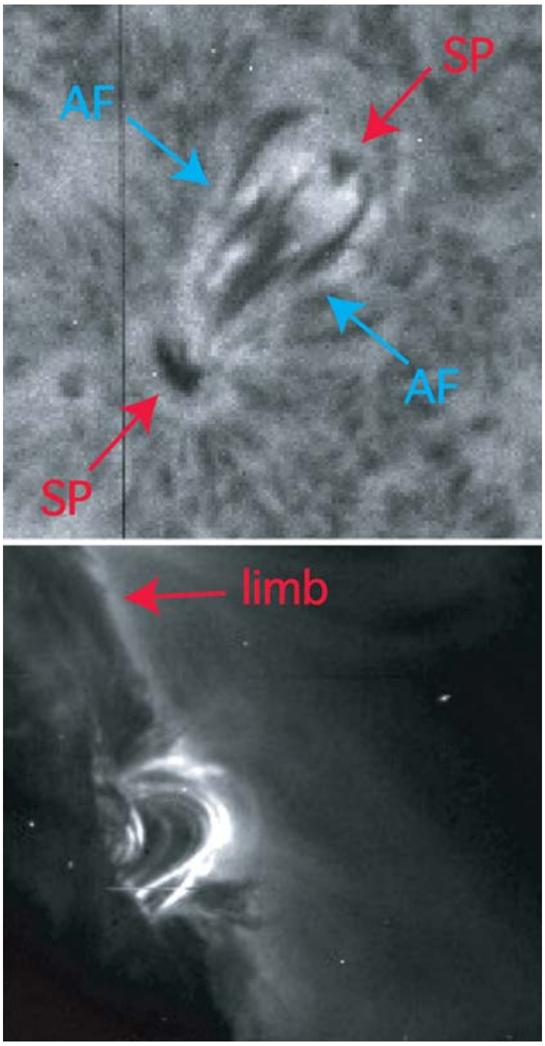

Fig. 2 Observations of emerging flux regions. The upper panel is H-alpha images taken by the Domeless Solar Telescope at Hida Observatory, Kyoto University (courtesy of H. Kurokawa and A. Edamura). SP and AF indicate sunspots and arch filaments, respectively. The lower panel is an extreme-ultraviolet image of an emerging flux region near the solar limb, taken by TRACE spacecraft.

at Hida observatory, Kyoto University. Prominent features are two sunspots (marked as "SP") with opposite magnetic polarities and dark, filamentary structure called arch filaments (marked as "AF") connecting the sunspots. Arch filaments visualize the magnetic field lines that are loaded with cold ($T = 10^4$ K) and dense plasma. Although they have been known for decades and very common in EFRs [10], the reason why only selected field line are loaded with dense plasma have not been clarified.

The lower panel of Fig. 2 shows an extreme-ultraviolet (EUV) image of an EFR near the solar limb taken by TRACE spacecraft. Many Ω-shaped bright and dark loops are clearly seen. The bright loops are hot (10^6 K) and appear in emission in spectral lines in EUV, while the dark loops are cold ($T = 10^4$ K) and appear in absorption in the EUV lines. This observation strongly suggests that heating in the EFR occurs spatially intermittent way.

In order to investigate the origin of such fine structures in EFRs, we have carried out high-resolution magnetohydrodynamic (MHD) simulations on the Earth Simulator [11, 12]. This work is a part of the Earth Simulator project "Cosmic Structure Formation and Dynamics (Project Representative: R. Matsumoto)".

2. Numerical model

The basic equations are non-linear, compressible magnetohydrodynamic equations of an ideal gas. Effects of radiation, thermal conduction and viscosity are neglected. Model of resistivity is essentially important to treat the magnetic reconnection and heating. We adopt an anomalous resistivity model in which the resistivity is enhanced where current density is large and mass density is small [13]. Numerical code is the modified Lax-Wendroff version of CANS (Coordinated Astronomical Numerical Softwares), which is parallelized using MPI and tuned to run effectively on the Earth Simulator.

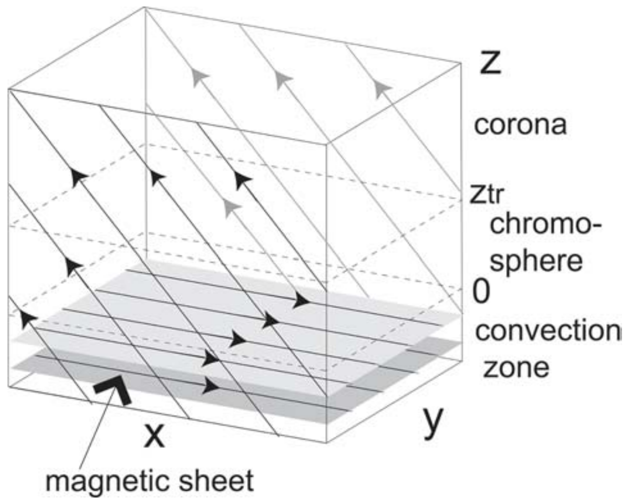

Fig. 3 Schematic illustration of the initial condition.

The simulation domain is a three-dimensional box with Cartesian coordinate including the upper convection zone, photosphere, chromosphere and the corona. A magnetic flux sheet is embedded in the initial convection zone, and there is an ambient magnetic field in the corona. The size of the domain corresponds to 50000 km along the flux sheet (*x*), 27000 km in vertical direction (*z*), and 16000 km in the third direction (*y*). The initial condition is illustrated in Fig. 3. A small perturbation is given in the central part of the flux sheet to excite the Parker instability.

The number of grid points is (N_x, N_y, N_z) = (800, 400, 620). This corresponds to Δy = 40 km, which is enough to resolve the typical size of filamentary structure (a few thousands km) in the emerging flux regions. It should be noted that existence of finer structures as small as 1 km have been inferred from measurement of radio propagation and scattering [14]. The resolution of the present simulation is not enough to resolve such ultra-fine structure. However, we emphasize that our simulation has unprecedentedly high resolution among the solar magnetohydrodynamic simulations. For the fist time, it demonstrated the development of fine structure as a result of global dynamics of the emerging flux in a self-consistent way. In this sense we have made qualitative progress from previous simulations owing to the computational resources of the Earth Simulator. For typical simulations we used 20 nodes of the Earth Simulator for about 8 hours. See reference [12] for the details of the simulation model.

3. Results

The general evolution of the emerging flux is shown in Fig. 4. The panels (a)–(c) show the temporal evolution of selected magnetic field lines and the plasma density distribution (color). At first a small Ω-shaped loop is seen in the central part of the flux sheet where the perturbation was given (panel a). Since the plasma cannot move across the magnetic field, the plasma at the top of the Ω-loop slides down along the magnetic field. The draining of the plasma along the magnetic field enhances the buoyancy

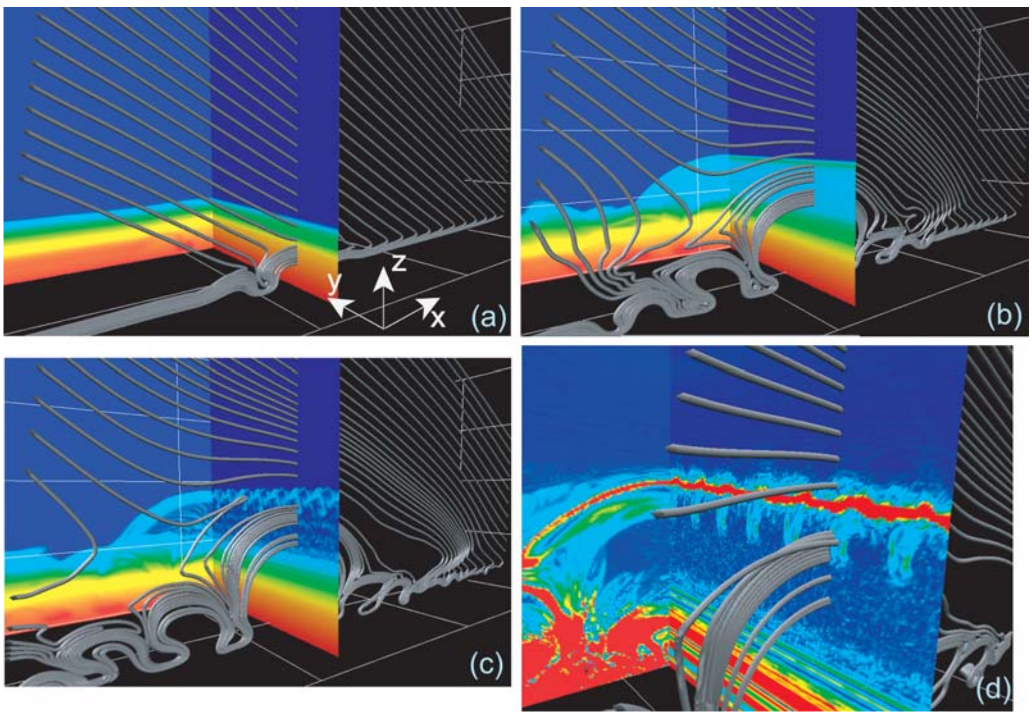

Fig. 4 Three-dimensional visualization of the simulation result, showing a set of magnetic field lines, density distribution (panels a, b, and c), and current density distribution (panel d). The times are t = 400, 750, and 800 sec for panels (a), (b), and (c), respectively. The time of panel (d) is also t = 800 sec.

of the loop, thus there is a positive feedback between the draining and the rising of the loop. This is the basic mechanism of the Parker instability [4, 5]. The expansion of the loop continues in a self-similar way and eventually forms large Ω-loops in the corona [5].

An interesting feature seen in panels (b) and (c) is the enhancement of density at the top of the Ω-loop. This dense sheet of the plasma is supported by the magnetic field, and because of this top-heavy configuration the top of the emerging flux (Ω-loop) is unstable for the magnetic Rayleigh-Taylor instability. Bending of the field lines is suppressed by magnetic tension, and hence only the interchange modes (i.e., the wave vector is perpendicular to the magnetic field) can grow [15]. This is clearly seen in panels (b) and (c); the density distribution on the y-z plane shows interchanging, turbulent structure, while on the x-z plane the density is smoothly distributed. Thus the resulting structure is dense filaments along the magnetic field. Fig. 5 shows the isosurfaces of density that visualize the dense filaments in the emerging flux. These filaments are remarkably similar to the arch filaments system shown in Fig. 2.

The magnetic Rayleigh-Taylor instability also creates small-scale electric current in the emerging flux. The color in panel (d) of Fig. 4 shows the current density distribution at the same time as panel (c). The strongest current sheet (shown in red in the figure) is that between the emerging flux and the ambient magnetic field in the corona, but small-scale, filamentary current sheets are also formed inside the emerging flux (green and yellow). Such filamentary current sheets are mainly formed in the periphery of the dense filaments. Although the coronal heating mechanism is still a controversial problem, dissipation of small-scale current sheets are believed to be one of the promising mechanism [16]. Rapid dissipation of the small-scale current sheets will heat the tenuous plasma between the dense filaments, which gives a natural explanation of intermittent heating and coexistence of hot and cold loops shown in the EUV image (see Fig. 2).

Another interesting point in our simulation is magnetic reconnection between the emerging flux and the ambient coronal field. Magnetic reconnection is the process in which anti-parallel magnetic field lines reconnect and change the connectivity, and strong plasma heating and acceleration occur [13]. It plays a key role in many explosive events in astrophysical, space, and laboratory plasmas including solar flares [17]. Magnetic reconnection associated with emerging flux has been studied extensively by numerical simulations [7, 18, 19].

Fig. 6 shows a reconnection event in the simulation. The blue transparent surface is the isosurface of magnetic field strength, and the arrows show the plasma velocity. Magnetic reconnection occurs at the top of the Ω-shaped emerging flux, where we can see a pair of reconnected, V-shaped field lines. These reconnected field lines accelerates the plasma like a slingshot by their own tension, creating the oppositely directed plasma flow. Such reconnection explains small flares and jet phenomena observed in the Sun [20, 21].

A new finding in our 3D simulation is the fine structure

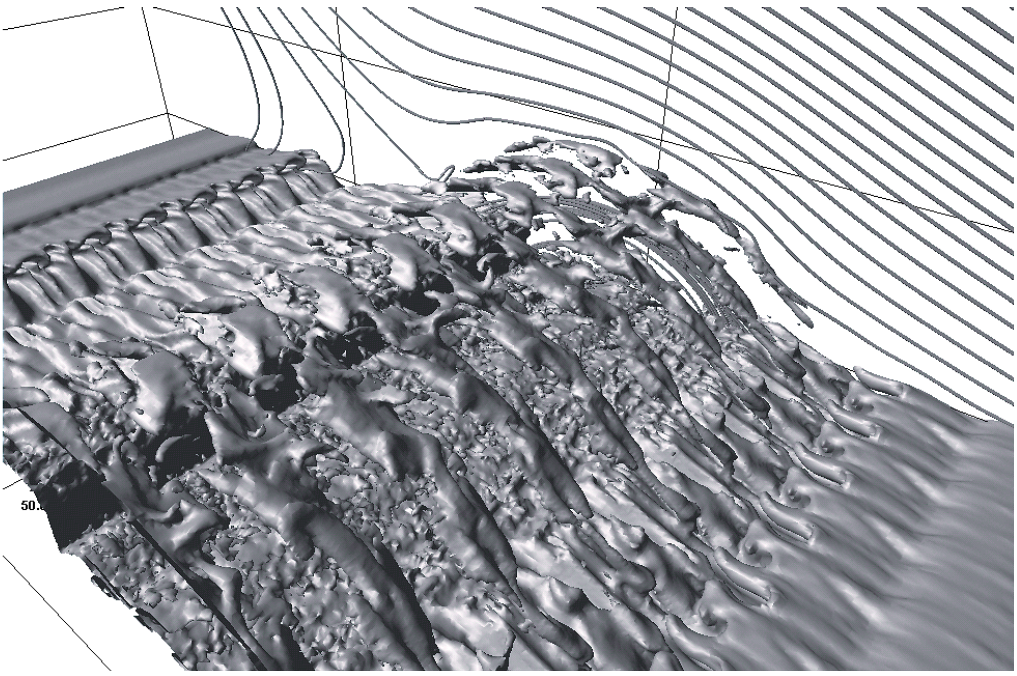

Fig. 5 Isosurface of density showing the dense filaments in the emerging flux.

in the jets. Since the interchanging structure is growing in the emerging flux, the current sheet between the emerging flux and the ambient field also becomes turbulent. Then the anomalous resistivity is locally enhanced in the current sheet, resulting in a patchy, spatially intermittent reconnection [11]. The structure of the reconnection jet is visualized in Fig. 7. The orange and yellow surfaces are the isosurfaces of the magnitude of the velocity $|\boldsymbol{V}|$, corresponding to 60 and 120 km s^{-1}, respectively. Similar fine structures are actually quite common, not only in EFRs but also various reconnection-related events such as flares.

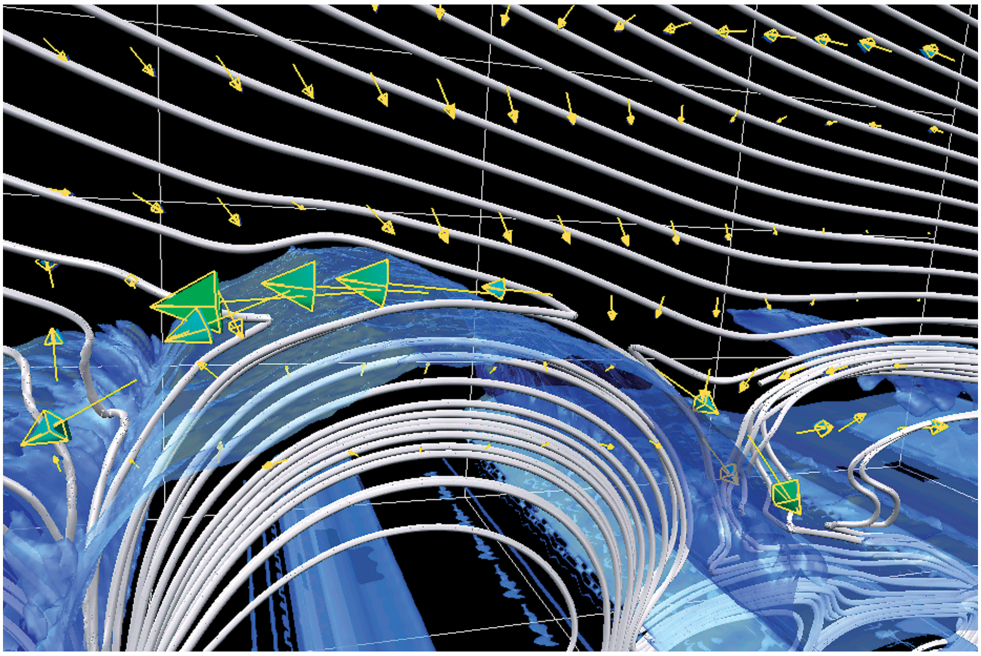

Fig. 6 The vicinity of the reconnection region. Shown in the figure are magnetic field lines, velocity vectors, and isosuraface of magnetic field strength.

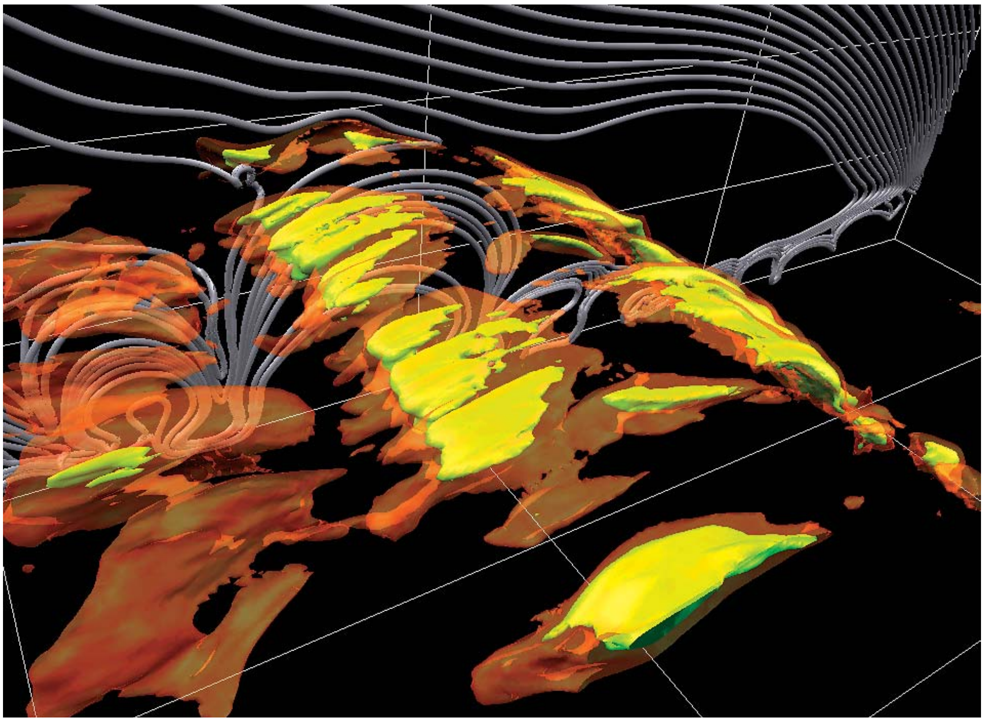

Fig. 7 Structure of the reconnection jets. The orange and yellow surfaces are the isosurfaces of the magnitude of velocity, corresponding to 60 and 120 km s^{-1}, respectively.

4. Conclusions

We have carried out high-resolution MHD simulations of an emerging flux and associated magnetic reconnection in the solar atmosphere. The high performance of the Earth Simulator has enabled us to simulate the formation of fine structure as a result of global dynamics in a self-consistent way. We have found (1) the origin of filamentary structure in EFRs such as arch filament systems is the magnetic Rayleigh-Taylor instability, (2) small scale currents are formed in the emerging flux, which explains the intermittent coronal heating, and (3) magnetic reconnection also occurs in a spatially intermittent way.

One of the fundamental problems in the physics of magnetic reconnection is the huge scale gap between the size of the system (typically 10000 km in the solar corona) and the microscopic scale in which the anomalous resistivity originates (typically 1 m in the solar corona). The present simulation demonstrates, for the first time, the self-consistent excitation of MHD turbulence in the current sheet and the resultant fine structure in the reconnection region. This provides a way to approach to the smaller scales (though still MHD), and may give us a clue to understand the scale gap problem in magnetic reconnection.

(This article is reviewed by Dr. Tetsuya Sato.)

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