VISUALIZATION OF THE FLUX ROPE GENERATION PROCESS USING LARGE QUANTITIES OF MHD SIMULATION DATA

Y Kubota[1]*, K Yamamoto[1], K Fukazawa[2], and K T Murata[1]

[1]*National Institute of Information and Communications Technology, Tokyo, Japan*
**Email: ykubota@nict.go.jp*
Emails: kaz-y@nict.go.jp, ken.murata@nict.go.jp
[2]*Research Institute for Information Technology, Kyushu University, Fukuoka, Japan*
Email: fukazawa@cc.kyushu-u.ac.jp

ABSTRACT

We present a new concept of analysis using visualization of large quantities of simulation data. The time development of 3D objects with high temporal resolution provides the opportunity for scientific discovery. We visualize large quantities of simulation data using the visualization application 'Virtual Aurora' based on AVS (Advanced Visual Systems) and the parallel distributed processing at “Space Weather Cloud” in NICT based on Gfarm technology. We introduce two results of high temporal resolution visualization: the magnetic flux rope generation process and dayside reconnection using a system of magnetic field line tracing.

Keywords: Visualization, Cloud computing system, Parallel distributed processing, Space weather, Reconnection, Magnetohydrodynamics simulation, Magnetosphere

1 INTRODUCTION

As supercomputer capacity increases, we can work with high precision simulation data when we need to visualize large quantities of simulation data by using 3D visualization techniques. Matsuoka et al. (2008) analyzed 3D structures of magnetic flux rope in the terrestrial magnetosphere by using these techniques. However, these authors visualized simulation data in a specific time and space region because their computational resources had limits. We succeeded in visualizing throughout all time and space regions by using large systems and parallel distributed processing (Murata et al., 2011). Our visualization technique provides the opportunity for real scientific discovery because we can see small and large scale structures at the same time. We performed two types of visualization to show two different methods of drawing magnetic field lines. In the first, the starting points of the magnetic field lines were fixed in time. In the other the starting points of the magnetic field lines moved with stream elements following their velocity. In the 'frozen-in' concept, the magnetic field line moved with stream elements except in a magnetic diffusion region. In the later visualization, there was magnetic field line tracing. In Section 2, we describe how to visualize all step data. In Section 3, we introduce visualization results of magnetic flux rope generation with fixed starting points and dayside magnetic reconnection by using magnetic field line tracing.

2 3D OBJECTS WITH HIGH TEMPORAL RESOLUTION

2.1 Global MHD simulation data

We used the data generated by a magnetohydrodynamics (MHD) simulation of the interaction between the solar wind and the terrestrial magnetosphere. The number of data points was 450×300×300 in Cartesian coordinates. The simulation covered a time interval of 2 hours with a time resolution of 0.5 sec. There were 14400 simulation steps. The space grid interval was $0.2R_E$, where R_E is the length of the Earth’s radius. The total data size was about 18TB. Data from the ACE satellite (Zwickl et al., 1998) with 5 minute intervals at the Galaxy15 (2010/4/5) event was used as the solar wind input. The outer boundary was where the variables were fixed for upstream and the variables were free for downstream. The inner boundary was where the variables had the same initial condition as the radius of $4R_E$. In the range from $4R_E$ to $5R_E$, the simulation values were smoothly combined with the initial values.

2.2 Visualization techniques using parallel distributed processing

In order to treat the large amount of data involved, we used the parallel distributed processing at "Space Weather Cloud" in NICT based on Gfarm technology. The number of processors was 100+ cores. We visualized the simulation data of the Galaxy event by drawing 1000+ field lines using the visualization application 'Virtual Aurora', which is based on AVS. The work flow of the visualization is shown in Figure 1. First we converted the simulation data to HDF format data for Virtual Aurora. Second we visualized the HDF format data using 'Virtual Aurora'. Third we output the result as time step 3D object files. Last we combined each time step 3D object into a high temporal resolution 3D object with a large amount of information. In case of magnetic field line tracing, we needed to read all files in order to trace the streak line. These work flows are complex for parallel distributed processing. In order to describe the work flow in the program, we used the Parallel Workflow extension for Rake (Pwrake) (Tanaka & Tatebe, 2010), which is a tool for parallel distributed processing. We described the flexible work flow by using Ruby (http://www.ruby-lang.org/en/). In order to look at the time development of a 3D object, e.g., a file size of a 2000 step GFA is 3GB, we developed the 64bit 3D object player in NICT, which can zoom on specific objects and easily change the view-direction.

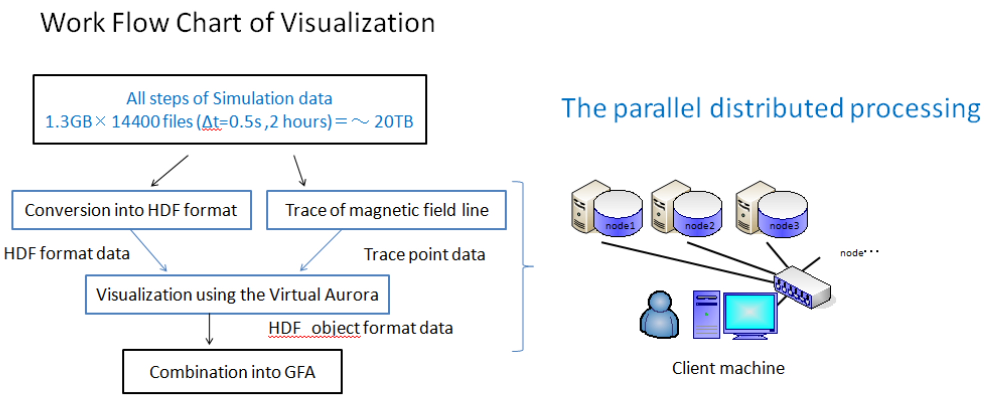

Figure 1. The work flow chart of the visualization using parallel distributed processing

3 Visualization of simulation results

The first visualization using the high temporal resolution visualization system with fixed starting points concerned the generation process of a flux rope, which is a small structure generated from a spiral field line by magnetic reconnection and related to a release of solar wind energy at the magnetotail. This knowledge can be acquired by looking at small and large scale structures with high temporal resolution. The second visualization using the system of magnetic field tracing concerned the dayside reconnection. In order to visualize the reconnection region, we needed to trace the magnetic field lines. This was done by visualizing the reconnection region.

3.1 Visualization of the magnetic flux rope

We showed the results of galaxy event simulation and observation for two hours. Figure 2 shows four snapshots of the simulation, the solar wind magnetic data observed by the ACE satellite, and the tail magnetic data observed by the GOES11 satellite (Connors et al., 2011). The snapshots show the pressure color contours of the equatorial and meridian cross section and the magnetic field line divided into open lines (red), closed lines (green), and detached lines (yellow) according to the topology of the field line. The intensity of the solar wind negative Bz increased at 8:00 UT as shown in the ACE magnetic data. The intensity of the magnetic field observed by GOES11 increased at 9:00 UT. This increase indicates dipolarization. In the MHD simulation, the topology of the magnetic field lines opened into a detached line because the field lines reconnected at about 8:36 UT, and a flux rope was generated. The flux rope released into interplanetary space at 8:41 UT. There was a difference of timing of about 30 minutes between the observational dipolarization and the flux rope release in the simulation. This difference arose because this simulation did not include the ionosphere effect on boundary conditions. A magnetic diffusion coefficient was uniform anywhere in the simulation, that is, reconnection occurred easily in the simulation. The simulation was consistent with the observation except for the difference in timing.

We were interested in the flux rope generation process. We investigated this process in high time resolution by visualizing this simulation using all step data. Figure 3 shows the topology of the magnetic field lines at flux rope generation. We visualized the first reconnection, that is, when the closed field line reconnected and changed into open field lines at 8:35:38.500 UT, as shown in Figure (c) and the enlarged figure. The open field line is the spiral structure, which generated the flux rope after 10 seconds, as shown in Figure (e). The open field lines reconnected and changed into detached field lines after 10 seconds, and the flux rope was released as shown in Figure (f). The topology of the magnetic field lines changed after 1 minute for the flux rope generation.

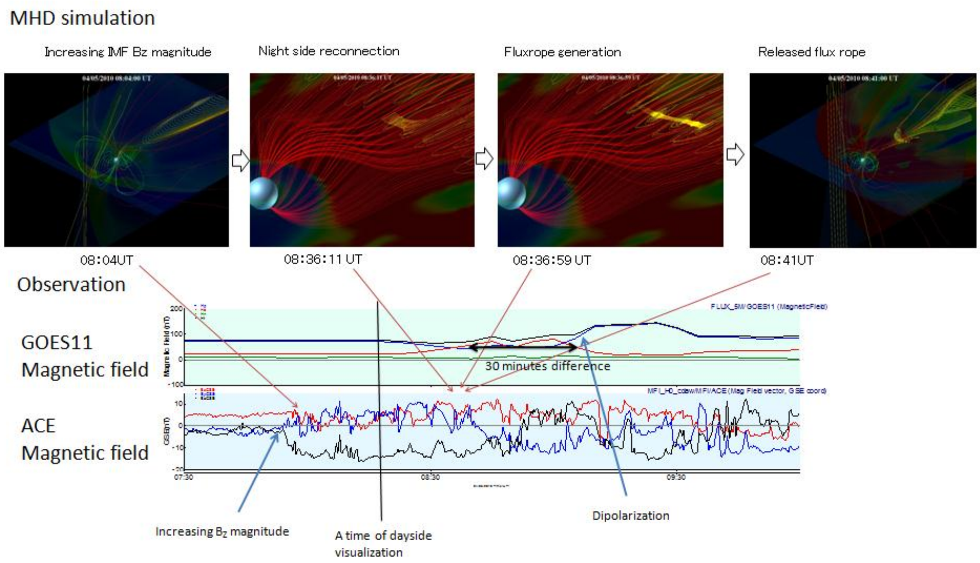

Figure 2. Comparison between the MHD simulation and the GOES11 observation at a galaxy event

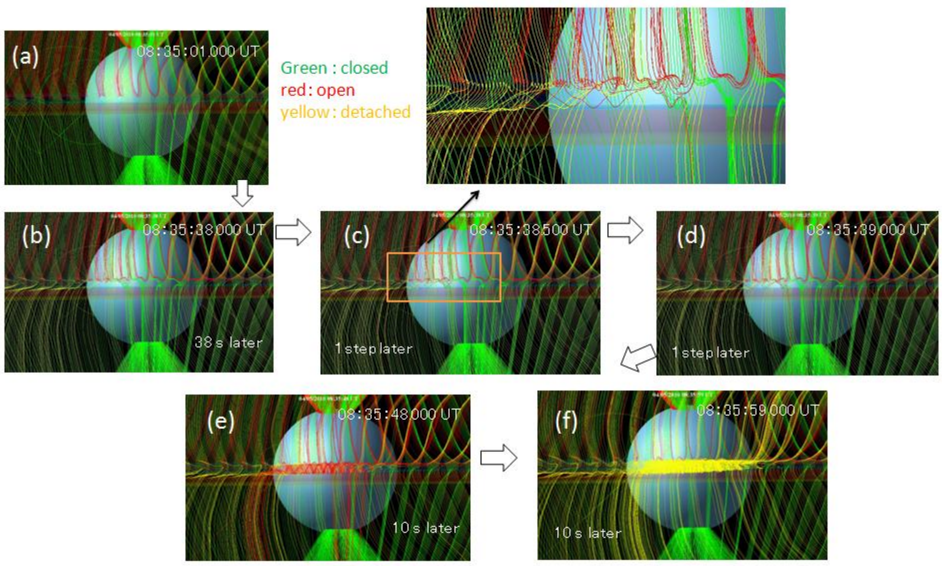

Figure 3. Topology of magnetic field lines during the 1 minute when the flux rope generated

3.2 Visualization of dayside reconnection using a system of magnetic field line tracing

The dayside magnetic reconnection is the main mechanism that transports solar wind energy into the magnetosphere. We visualized the reconnection region between the interplanetary magnetic field (IMF) and the terrestrial magnetic field by tracing the IMF. At first, we traced the IMF when the IMF was southward

(Bz=-12nT, By=5nT) at 8:20 UT. Figure 4 shows the dayside reconnection region. We viewed in the direction from the Sun to Earth. The blue sphere is the Earth. The yellow lines and the red lines are magnetic field lines. The topology of the field lines is indicated by the same colors as in Section 3.1. The yellow points are starting points for drawing the magnetic field line. The starting points are 11point (dawn to dusk) × 11point (north to south) and the interval is $2R_E$. Figure (a) shows that the magnetic field lines starting from two red circles are bent in the dawn-dusk direction in order to diffuse between the solar wind and the terrestrial field. The red square indicates a diffusion region. The diffusion region is from a subsolar point to $\pm 5R_E$ in the dawn-dusk direction. After 0.5 seconds, the field lines first reconnected with the terrestrial field line, as shown in Figure (b). The solar wind field lines reconnected with the terrestrial field through this diffusion region. After 10 seconds, the magnetic field lines in the region from the subsolar point to $\pm 5R_E$ in the dawn-dusk direction reconnected with the terrestrial field lines at the dayside magnetopause, as shown in Figure (c). In the region of the flank sides over $\pm 5R_E$, the magnetic field lines did not reconnect and were transported through the sheath region to the downstream.

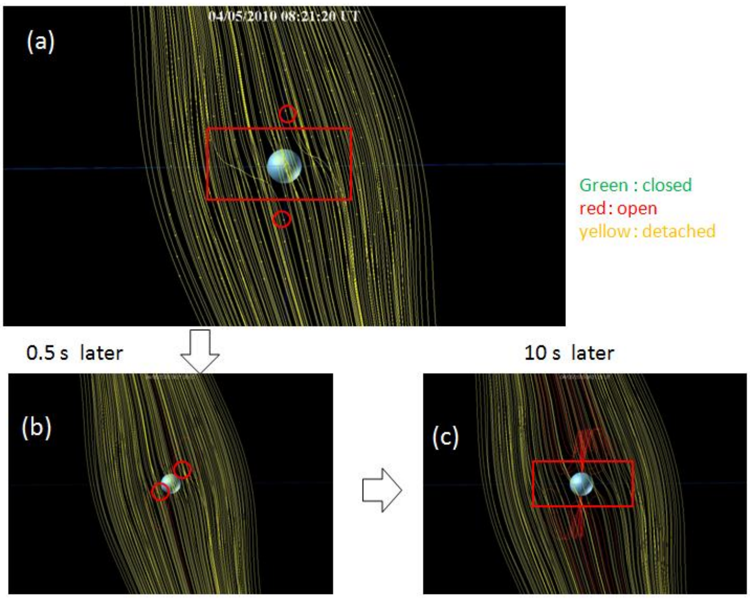

Figure 4. Visualization of the dayside reconnection region

4 CONCLUSION

We have visualized the results of an MHD simulation using two methods. These methods differ in treatment of the starting points as well as in high temporal resolution by using parallel distributed processing. First we visualized the generation of a flux rope for a galaxy event. We found that the topology of the flux rope's magnetic field lines changed over a period of one minute. Second we succeeded in visualizing a magnetic field line tracing to the MHD simulation data. We found that the magnetic field lines in the region from the subsolar point to $\pm 5R_E$ in the dawn-dusk direction reconnected at the dayside magnetopause and transported the nightside magnetosphere. In the region of flank sides over $\pm 5R_E$, magnetic field lines did not reconnect and were transported through the sheath region to the downstream.

5 ACKNOWLEDGEMENTS

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