MHD simulation of Kronian magnetosphere with high resolution solar wind data by Cassini

Keiichiro FUKAZAWA[1, 2, 3], Raymond J. WALKER[4], Stefan ERIKSSON[5]

1. Introduction

The vortex and turbulent convection are appeared in the Kronian magnetosphere for three IMF (no / southward / northward) cases in our early simulation results [*Fukazawa et al.*, 2007a]. Figure 1 shows the results of simulation with those IMF conditions. Panels (a), (b) and (c) are the plasma temperature with the plasma flow vector on the equatorial plane. In those panels the disturbed convection and vortices are found. In the observation *Masters et al.* [2009] studied Cassini magnetic field and thermal plasma observations at the dawn magnetopause to infer tailward propagating surface waves on the boundary and suggested that they were caused by the Kelvin-Helmholtz (K-H) instability. Recently we can simulate the Kronian magnetosphere with the fine resolution thanks to the large scale simulation project in Japan and found the clear vortices along both dawn and dusk magnetopause which may be related to the auroral emission for the northward IMF case [*Fukazawa et al.*, 2012]. However the influence of solar wind to the magnetospheric convection and dynamics of Saturn has not been understood.

In February 2008 Cassini observed the solar wind upstream the Saturn and Hubble Space Telescope (HST) observed the Kronian aurora simultaneously. In this study, to understand the real relationship between the solar wind effect and response of the Kronian magnetosphere, the high resolution MHD simulation of Saturn is performed using the supercomputer system at Kyushu University, which is Fujitsu PRIMERGY RX200S6, and the observed solar wind data by Cassini.

2. Simulation setting

Our Kronian simulation model is described in *Fukazawa et al.* [2007a; b, 2012] and *Walker et al.* [2011]. The high resolution Kronian magnetosphere was modeled on a $1802\times1202\times1202$ point Cartesian grid with grid spacing of 0.1 R_S (1 R_S = 60,268 km) thus the simulation domain covers the region, $-120 < X < 60$ R_S, $-60 < Y < 60$ R_S, $-60 < Z < 60$ R_S. In the simulation the magnetic field (**B**), velocity (**v**), mass density (ρ) and thermal pressure (p) are maintained at solar wind values at the upstream boundary. Free boundary conditions (plasmas freely leave the boundary) are used at the top, sides and downstream boundaries. Our simulation started from a static equilibrium that included

[1] Research Institute for Information Technology, Kyushu University
[2] International Center for Space Weather Science and Education, Kyushu University
[3] JST, CREST
[4] Institute of Geophysics and Planetary Physics, University of California, Los Angeles
[5] Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder

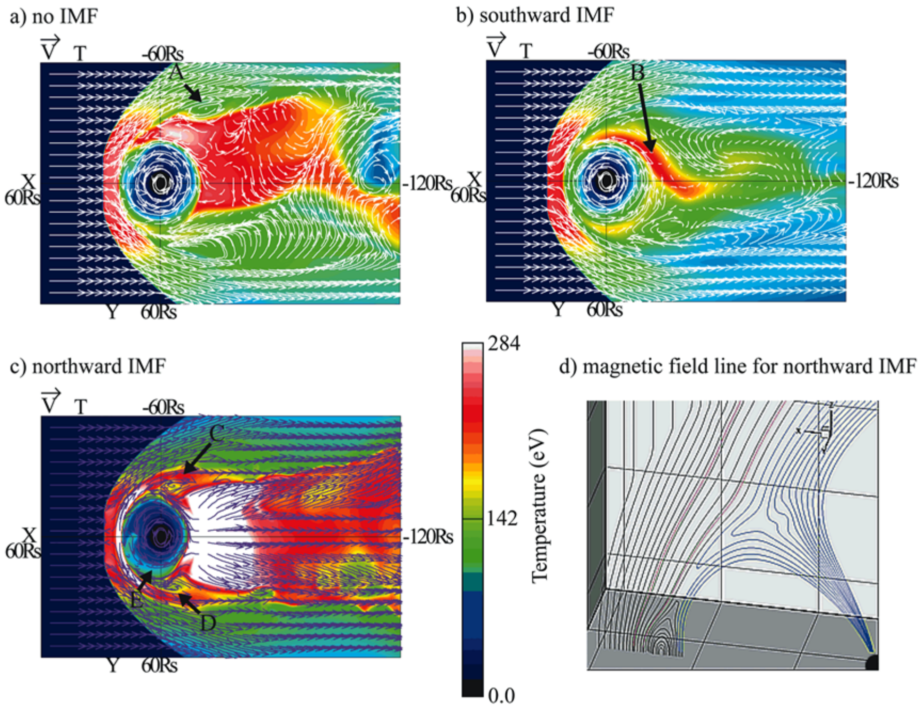

Figure 1. The temperature and flow vectors in the equatorial plane for the simulations with no IMF (a), southward (b) and northward IMF (c) [*Fukazawa et al.*, 2007a]. The temperature per atomic mass unit in eV is given by the color spectrogram. The black region in the center of the panels is inside the inner boundary of the simulation at 5 R_S. The lower right panel (d) contains magnetic field lines along the Sun-Saturn line for the northward IMF case.

corotating flows, pressure gradients, the $\mathbf{J} \times \mathbf{B}$ force and gravity. At the inner boundary (nearest Saturn) the parameters are fixed to those from the equilibrium evaluated at r = 5 R_S. The simulation quantities are connected with the inner boundary through a smooth transition region (5 < r < 6.5 R_S). The magnetic field of Saturn is directed oppositely to that at Earth. The normalization factors for **B**, **v**, ρ, and p are given by the dipole magnetic field (B_d = 21,084 nT [*Dougherty et al.*, 2005]), the Alfvén velocity (V_A) at the planetary surface V_A= 4,359 km s^{-1}, the plasma mass density of the ionosphere ρ_s = 1.67 $\times 10^{-17}$ kg m^{-3} and the magnetic pressure at the planetary surface P_S = 3.19 $\times$ 10^{-4} Pa.

The solar wind condition used in this study is come from the observation of Cassini between 2008/02/12/14:00 and 2008/02/13/02:00. Figure 2 shows the observed solar wind conditions of magnetic field, velocity, plasma density, dynamic pressure and temperature. Before performing the simulation using these solar wind conditions, we calculated the Kronian magnetosphere for 40 hours to reach the magnetosphere the quasi-steady state using the average solar wind condition.

The required memory size of computer from the simulation box in this study is 600GB and required calculation time is over one year, thus the calculation of this size was not possible to execute on the computer we used for our earlier simulations. Fortunately on the latest generation of supercomputers, we were able to run such a large simulation in approximately two months. We used 768 cores on the supercomputer at the Kyushu University.

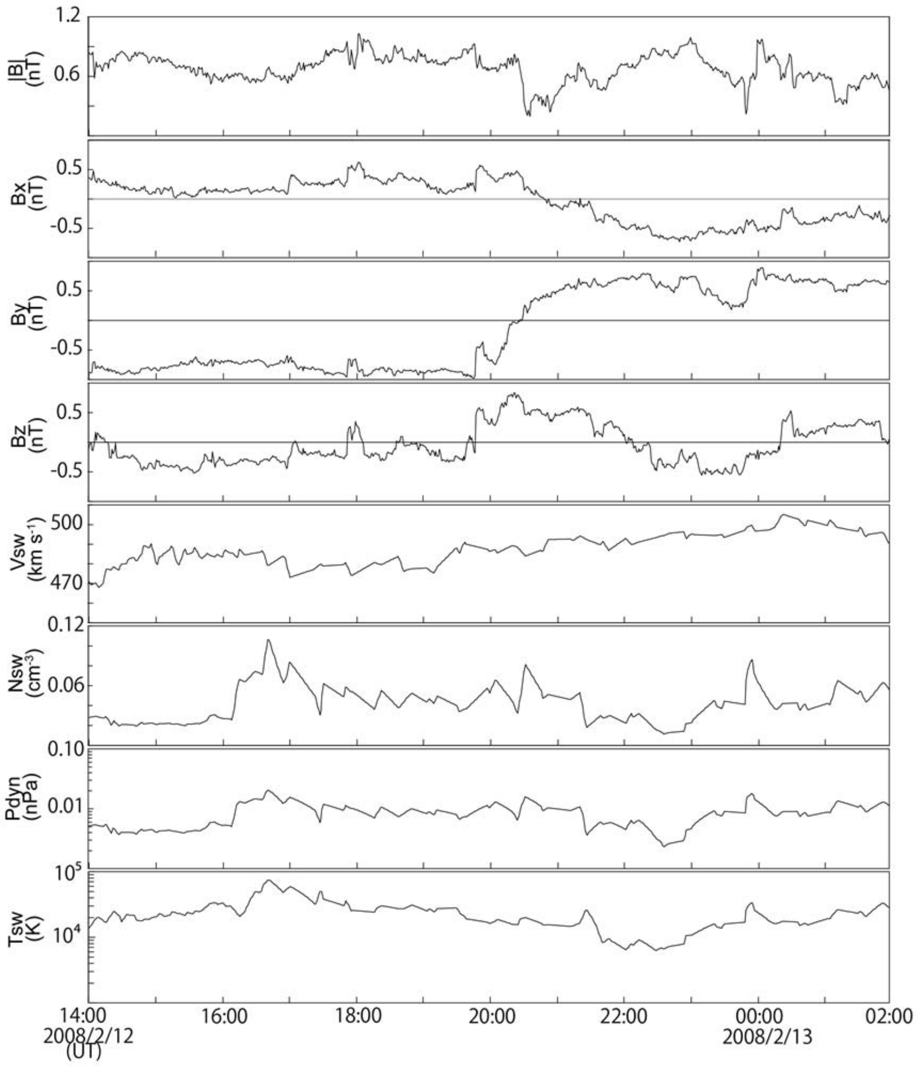

Figure 2. The solar wind conditions observed by the Cassini between 2008/02/12/14:00 and 2008/02/13/02:00 in the upstream of Saturn.

3. Simulation Results

Using the observed solar wind data, we calculated the Kronian magnetosphere for 12 hours. Dynamically changing solar wind makes the disturbed magnetospheric convection and several vortices in the magnetosphere. In addition the position of magnetopause is varied dynamically. Figure 3 shows three snapshots of simulation results. The color spectrum shows the plasma temperature with the plasma flow vector. In this figure it is found that the formation of vortices at dawn and dusk and they move into the tail.

To confirm the configuration of polar ionosphere, the energy flux and field-aligned currents (FACs) are calculated from the simulation results. Figure 4 shows the time series of energy flux in the southern hemisphere and Figure 5 shows the FACs in the southern hemisphere. From Fig. 4 when the shock of solar wind coming, the energy flux expand to the lower latitude around 12LT (local time), then its expansion travels through the dawn and dusk to the midnight. In addition, the shock makes the strong FACs and patchy like configuration around 12LT. After 22:20, strong upward FAC is formed between 80° and 85 °.

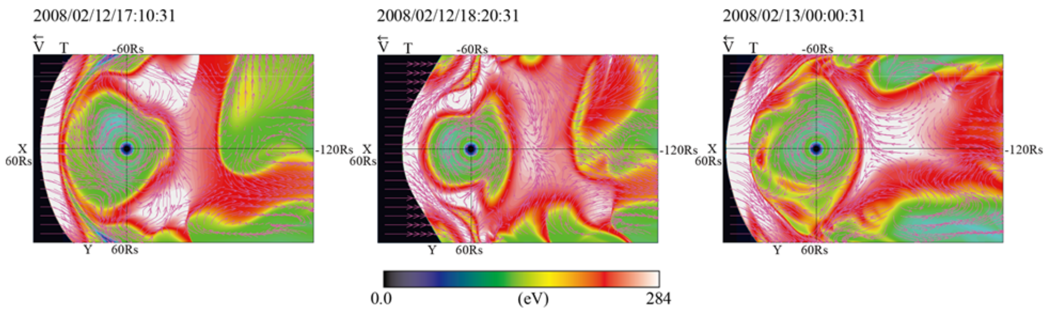

Figure 3. Time series of temperature and flow vectors in the equatorial plane. The temperature per atomic mass unit in eV is given by the color spectrogram. The black region in the center of the panels is inside the inner boundary of the simulation at 5 R_S.

4. Comparison of Simulation with Observation

Clarke et al. [2009] report the sample UV images of Saturn's South Pole in February 2008 with quiet and disturbed conditions including the period of this study. Figure 6 is the HST UV image at 2008/02/13/00:00 from Figure 3 in *Clarke et al.* [2009]. In this figure there are two enhancements of auroral emission in the high latitude (around 85°) and lower latitude (80°) at the dawn side. This UV

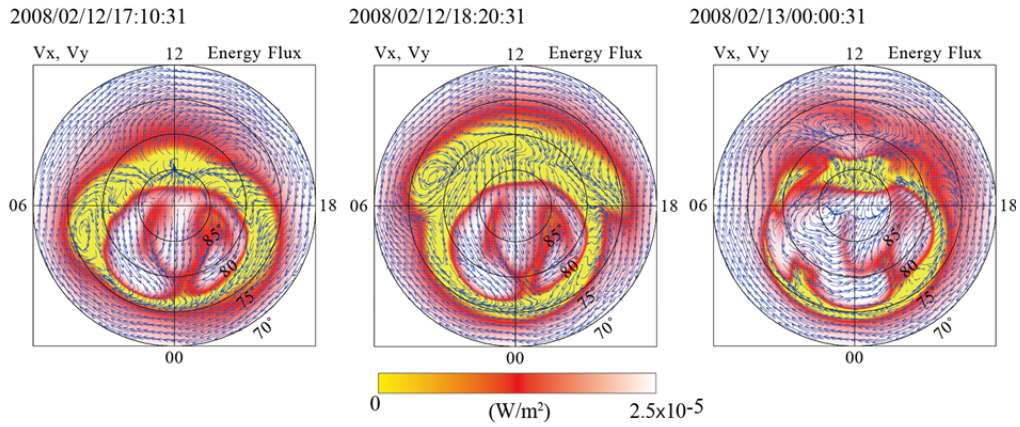

Figure 4. Energy flux and plasma velocity in the polar cap mapped along magnetic field lines from the inner boundary of the simulation to the southern ionosphere at the same time as in Figure 3.

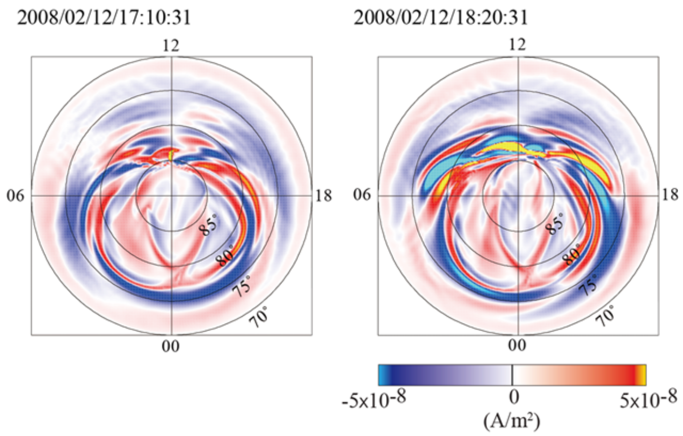

Figure 5. Field-aligned currents with blue representing the upward (away from Saturn) currents and red downward currents. The deeper colors indicate higher current densities. Light blue and yellow are the highest currents. The value of the currents is proportional to the Pederson conductance and here we set it to 1 S to understand the rate of variation easily.

image time is corresponding to the right panel of Figure 5. In general an upward FAC affects the aurora. In the results of FACs there are two strong upward FACs at the noon (00LT) around 85° and the strong upward FAC distribute from less than 85° to 75° at the dawn side. They may be corresponding to the brightening of observation.

5. Summary

In this study we perform the simulation of Kronian magnetosphere using the solar wind data observed by Cassini. Using the real solar wind data by Cassini, we can obtain the simulation results of dynamically changing magnetopause and large vortices in the magnetosphere. To compare a snapshot of simulation results of FACs and the image of HST observation, we found the good similarity of feature between them. However we should examine the results quantitatively more in detail.

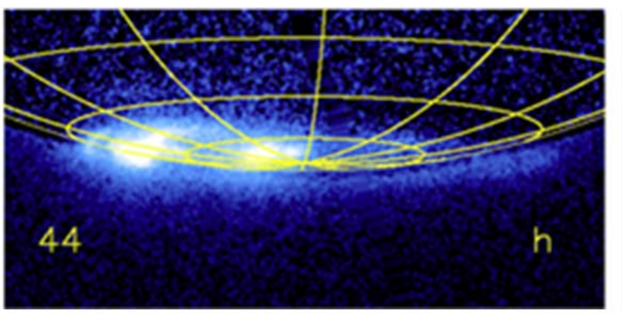

Figure 6. UV images of Saturn's south pole at 2008/02/13/00:00 from Figure 3 in *Clarke et al.* [2009].

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