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# Spontaneous Variation in a Rotating Magnetosphere

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## Abstract

The spatiotemporal structure in a rotating magnetospheric system is investigated by using the global magnetohydrodynamic (MHD) simulation of the interaction between the rotating magnetosphere and the external plasma flow. The results of the simulation indicate that the global structure of the dawn side magnetopause, where the external flow collides with the rotating flow in the magnetosphere, is temporally varied even when the condition of the external flow is steady, especially in the case imposing relatively low speed external flow. The mechanism of the spontaneous variation may be determined by the competitive process between the external flow, the rotating flow, and the magnetic pressure at the dawn side magnetosphere.

## Keywords:

magnetosphere, planetary rotation, spontaneous variation, MHD, numerical simulation

## 1. Introduction

The magnetosphere is formed by the nonlinear interaction between the intrinsic magnetic field of the celestial body and the state of surrounding plasmas. In the Earth's magnetosphere, the solar wind, which is supersonic/super-Alfvénic plasma flow blowing from the sun, compresses the dipole magnetic field of the Earth and deforms it into a blunt shape, where the dynamic pressure of the external flow is balanced with the magnetic pressure of the compressed magnetic field [1,2]. Thus, we can simply estimate the characteristic scale to the magnetopause, $R_{\mathrm{MP}}$, by the balanced equation of the pressures at the interface. As for the Earth's magnetosphere, this was essentially confirmed by the observation [3]. On the other hand, the Jovian magnetosphere is strongly affected by the rapid rotation of Jupiter. Indeed, the plasma disc, where dense and cool plasmas are confined in a disc-like region detected by in situ observations, must be formed by the rotation of Jupiter [4]. Furthermore, temporal variation of the position of the bow shock and the magnetopause was observed for ranges about 50 $R_{\mathrm{J}}$ to more than 100 $R_{\mathrm{J}}$ [5]. Until now the mechanism of the variation has not been understood completely, although the large variation more than 50 $R_{\mathrm{J}}$ may be caused by the large variation of the dynamic pressureof the solar wind [6]. Since the distance to the magnetopause, especially in the expanded state, is inconsistent with estimated $R_{\mathrm{MP}}$, the scale to the Jovian magnetopause is characterized by the interaction not only with the solar wind but also with the rotation. Thus, the rotation must induce the distinctive features of the magnetospheric structure and the dynamics. In the rotating magnetospheric system, we can introduce another characteristic scale, $R_{\mathrm{A}}$, at which the kinetic energy of the corotating plasma is equal to the magnetic energy [7]. In the Jovian magnetosphere, $R_{\mathrm{A}}$ is estimated as a match for $R_{\mathrm{MP}}$, while $R_{\mathrm{A}}$ is thought to be extremely greater than $R_{\mathrm{MP}}$ in the Earth's magnetosphere if the corotation could be assumed. Thus, the researches of the Jovian magnetosphere will give new insight of the magnetospheric physics because

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*Corresponding author's e-mail: miyoshi@sci.hiroshima-u.ac.jp the effects of the rotation, the external flow, and the intrinsic magnetic field are competed with each other. Although several global models for the Jovian magnetosphere have been proposed based on local theories or it situ observations [7-11], even the global structure is still uncertain due to the nonlinearity and the three-dimensionality. Recently, first simulation studies for the global structure of the Jovian magnetosphere, where the interaction between the rotating magnetosphere and the solar wind is taken into account, have been carried out by two groups independently [12-14]. In their models, the magnetospheric structure such as the plasma disc was realized self-consistently. The dynamics of the global structure, however, was not clarified completely. Therefore, in this paper, the dynamics of the global structure of the previous model [12,13] is investigated in detail, and the spontaneous variation model of the rotating magnetosphere is proposed.

## 2. Simulation Model

The simulation model in the present study is the same as in the previous papers [12,13]. The model with the boundary conditions is summarized as follows: The magnetohydrodynamic (MHD) equations are adopted as the basic equations since we concentrate our attention on the global structure and the dynamics at present. The MHD equations are numerically solved by employing the total variation diminishing (TVD) scheme based on the eight-waves characteristic form of the MHD equations [15]. Since we focus on the global structure of the Jovian magnetosphere, the simulation domain is given by a large rectangular box, $(-350\ R_J, -250\ R_J, 0) \le (x,y,z) \le (150\ R_J, 250\ R_J, 250\ R_J)$, in which the inner half sphere of the radius $r_0 = 30\ R_J$ is clipped off. Here we use the solar-magnetospheric coordinate, where the $x$, $y$, and $z$ point to the sun, the dusk and the north, respectively. In order to perform the present simulation, following boundary conditions are imposed: The mirror boundary condition is adopted at the equatorial plane. The boundary condition on the top, the side, and the tail walls is given by the free boundary condition. The inflow parameters are fixed at the front boundary as given in Table 1, where no IMF is assumed at present. Also, since we take an interest in the global structure and its dynamics of the rotating magnetosphere, the inner boundary at $r_0$ is simply regarded as a plasma bath. Thus, the influence of the plasma source, i.e., Io torus, is averaged out on the inner sphere. The inner boundary condition of the density and the pressure is switched depending on the sign of the radial velocity $V_r$, such that $\rho = n_0 m_i$, $P = P_0$ for $V_r > 0$, and $\partial\rho/\partial r = 0$, $\partial P/\partial r = 0$ for $V_r \le 0$, where $m_i$ is the mass of proton, $n_0 = 0.1\ \mathrm{cm}^3$ and $P_0 = 1.1 \times 10^{-12}\ \mathrm{cm}^3$, respectively. These parameters $n_0$ and $P_0$ are chosen from in situ measurements at the middle portion of the Jovian magnetosphere [16]. The velocity parallel to the magnetic field, $V_\parallel = \boldsymbol{V}\cdot\boldsymbol{B}/B$, at the inner boundary is determined such as to satisfy the empirical relation $\partial(r^2\rho V_\parallel)/\partial r = 0$. The velocity perpendicular to the magnetic field, $\boldsymbol{V}_\perp = \boldsymbol{V} - V_\parallel\boldsymbol{B}/B$, is determined by $\boldsymbol{V}_\perp = \boldsymbol{E} \times \boldsymbol{B}/B^2$, where $\boldsymbol{E} = -(\boldsymbol{\Omega}_0 \times \boldsymbol{r}_0) \times \boldsymbol{B}$. The angular velocity $\boldsymbol{\Omega}_0$ at $r_0$ is set to a half of the Jovian angular velocity, $\boldsymbol{\Omega}_J = (2\pi/10.0)\boldsymbol{e}_z/\mathrm{h}$, based on the observation from the inner to the middle Jovian magnetosphere [4]. For these parameters, $R_{MP}$ is estimated approximately as 43.2 $R_J$ and 47.5 $R_J$ in case H and L, respectively. Also, $R_A$ is evaluated as about 47.9 $R_J$ in both cases. Thus, the two characteristic scales are the same order, and the difference between the parameters for case H and L seems to be slight.

Table 1 Solar wind parameters in simulation runs.

| case | $n$ (/cm$^3$) | $V_x$ (km/s) | $B_z$ (nT) | $T$ (K) |
|---|---|---|---|---|
| L | 0.1 | −300 | 0 | $4 \times 10^4$ |
| H | 0.1 | −400 | 0 | $4 \times 10^4$ |

## 3. Results and Discussion

The global structure of the magnetosphere seems to achieve the quasi-steady state in both cases H and L by the elapsed time about 30 to 40 hours. In the previous papers [12,13], the spatial structure of the rotating magnetosphere in the quasi-steady state was investigated in detail. However, the detailed analyses for the time development of the global structure indicate the dynamic feature of the rotating magnetosphere although the fundamental structure, such as the topology of the magnetic field lines of force as seen in Plate 1 of [13], does not change essentially over in the quasi-steady state. From the view of the global model proposed as Plate 7 of [13], the magnetosphere over the dawn to the noon region shows the complicated structure, where the solar wind collides with the rotating flow in the magnetosphere. Also in that area, the *sponginess* of the magnetosphere was observed by in situ observations [5]. Thus, in Fig. 1, we show the time evolution of the distance to the magnetopause $R_{MP}$ at 0730 LT in case H and L. It is found, in case L, that the distance to the magnetopause at the prenoon region is temporally varied, and rapid shrinkage of the magnetopause subsequent to slow expansion may be recurrent even when the condition of the solar wind is steady. This may be one of the causes of the fluctuation in the Jovian magnetosphere detected at the dawn side [5]. On the other hand, the evident variation of the magnetopause is not observed in case H. The difference of these results may arise from the fact that, in the former case, the internal magnetospheric state shows the dynamically dominant state, while the internal state is magnetically dominant at the day side magnetosphere in the latter case, as discussed in the previous papers (see Plate 3 of [13]). Here, in order to clarify the process of the spontaneous variation in case L, the structure of the magnetic field lines of force at the expanded and the shrinking state is displayed in Fig. 2. As seen in Fig. 2 (a), the magnetic field lines tend to pile up on the dawn side in the expanded state. In the shrinking state in Fig. 2 (b), on the other hand, strongly accumulated field lines on the dawn in the expanded state are partly relaxed. As a confirmation of the partial relaxation, it is indicated in Fig. 3 (a) that the intensity of the magnetic field on the magnetopause at 0730 LT is weakened for the shrinking phase. Moreover, at the downstream of the rotating flow (1000 LT), the strong azimuthal flow is detected just after a little delay from the shrinking phase at 0730 LT. Thus, the mechanism of the spontaneous variation may be explained as follows (Fig. 4): As the first stage, in case L, the magnetic field lines of force frozen-in in the rotating plasmas are advected toward and accumulated at the dawn side, where the plasma flow is stagnant, due to the dynamically dominant state (Figs. 7 and 8 of [12]). Therefore, the magnetic pressure at the dawn side becomes large and gradually enlarges the magnetopause. Also for this phase, the magnetic field lines anchored to the dawn side magnetosphere continue to be bent. Then, when the direction of the force deviated from the equilibrium on the dawn side magnetopause is changed from the normal direction to the tangential direction, the

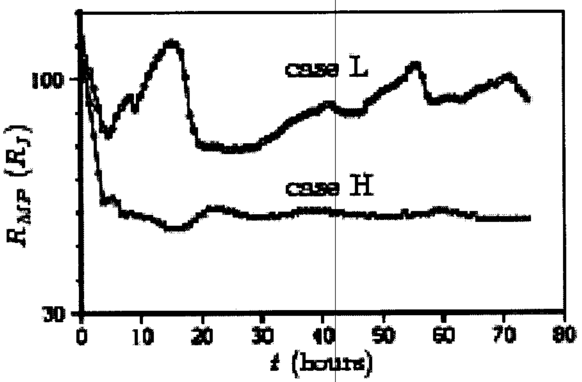

Fig. 1 Time history of the position of the magnetopause at 0730 LT in case H and L.

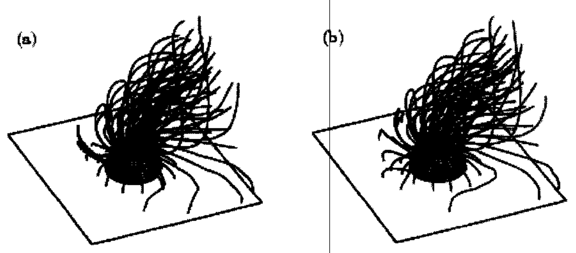

Fig. 2 Three-dimensional structure of the magnetic field lines of force in case L at (a) $t$ = 55.2 and (b) $t$ = 56.7, respectively.

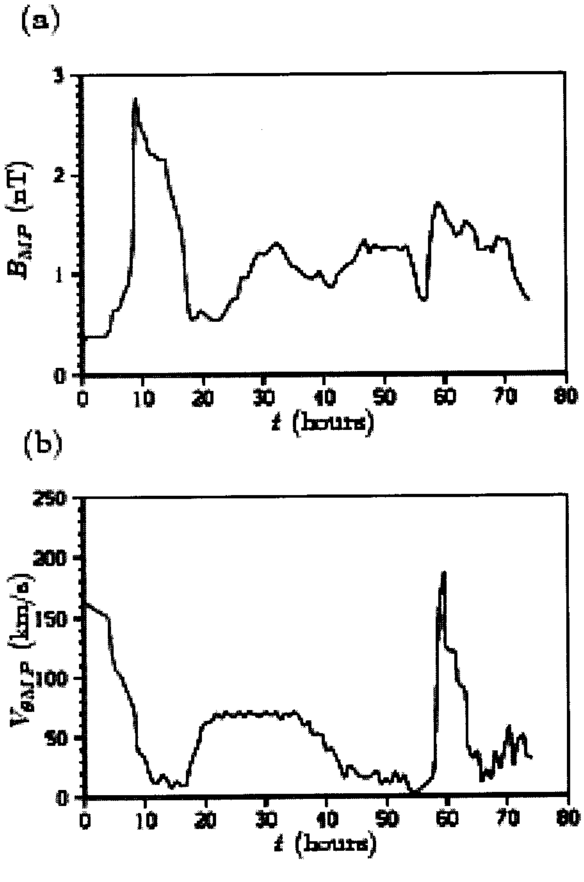

Fig. 3 Time history of (a) the intensity of the magnetic field at 0730 LT and (b) the azimuthal velocity at 1000 LT, respectively, just inside the magnetopause.

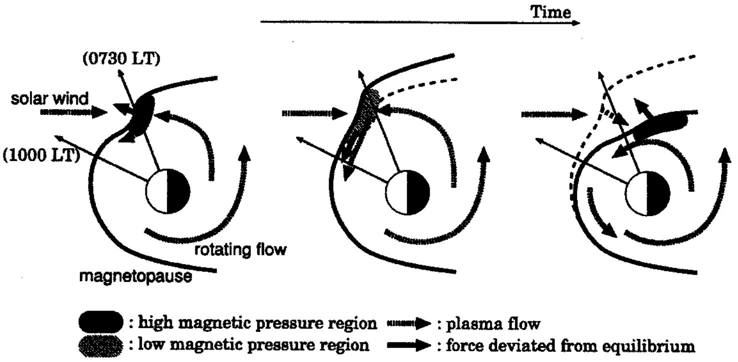

Fig. 4 Schematic model for the spontaneous variation in the rotating magnetosphere.

accumulated lines rush into the downstream by the magnetic tension force in the shrinking phase. Here the change may be related to the structure of the *dip* at the dawn. Thus, the magnetic pressure at the prenoon sector rapidly descends, and as a result, the boundary of the magnetosphere supported by the magnetic pressure rapidly shrinks. After that, the magnetic pressure recovers almost same level as the first stage immediately since the magnetic pressure must balance with the dynamic pressure. Subsequently, the same processes may be repeated intermittently.

## 4. Summary

The dynamics of the rotating magnetosphere interacting with the external flow was investigated by using the global MHD simulation. Especially, the detailed analyses for the time development of the magnetospheric model in previous papers [12,13] were made. In case L, the spontaneous variation of the magnetospheric structure was observed even when the condition of the external flow is steady, while the evident variation could not be detected in case H. The difference of these results may be due to the difference of the internal magnetospheric states as pointed out in [13]. In regard to the variation, the correlation between the decrease of the magnetic intensity and the increase of the azimuthal velocity in the downstream was observed at the dawn to noon sector. Thus, the spontaneous variation in the rotating magnetospheric system may be caused by the competition between the dynamic pressure of the external plasma flow, that of the rotating flow, and the magnetic pressure at the dawn side magnetosphere.

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