Structure of the Jovian Magnetospheric Boundary Region

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A structure of the Jovian magnetospheric boundary region near the equatorial plane which is produced by the interaction between the solar wind plasma and the internal planetary wind plasma in the magnetodisc, has been studied. A possibility of the existence of the internal shock, as a innermost boundary between the planetary wind and the region of the intrinsic magnetic field, has been investigated theoretically using two dimensional Rankine-Hugoniot relation in MHD regime. The results of present numerical calculation for the internal shock indicate the asymmetrical characteristics; that is, the internal shock is strong in the dawn side of the Jovian magnetodisc, while the shock formed in the dusk side is weak and disappears at the intermediate position reflecting the azimuthally flowing nature of the Jovian disc wind.

A unique model of the Jovian low latitude magnetospheric boundary structure which consists of the double shock (bow shock and internal shock) and the double magnetopause (magnetopause and internal magnetopause), has been proposed. The data obtained by the in-situ observations suggest the existence of the theoretically proposed boundary structure. This coincidence suggests a indirect confirmation of the existence of the Jovian disc wind which is proposed on the theoretical base.

1. Introduction

Due to the high speed rotation with the intense magnetic field, the plasma in the Jovian magnetosphere is largely affected by the centrifugal force. Especially, over the region of the Alfvén limit, the magnetosphere is controlled by the outward flow motion of the plasma. The theoretical study has been carried out on the basis of the macroscopic MHD equations for the plasma flow which is predicted to be forming the magnetospheric disc wind in the equatorial region of the Jovian magnetosphere (OYA and AOYAMA, 1985). The numerical results from the theoretical studies indicate that there exist super magnetosonic flows when the solar wind pressure is not so as to compress the magnetopause into the planetary side, while the plasma flow becomes the breeze in the case of the high solar wind pressure. The position of the magnetopause is therefore intimately related to the rotation of the planet as the origin of the magnetic field and the solar wind condition. Considering the internal planetary wind the theoretical studies have also been made for the shape and position of the magnetopause around the equatorial region (AOYAMA and OYA, 1985). The studies
of the earth’s magnetopause are originally considered by Chapman and Ferraro (1930, 1931). Since then, many works (Ferraro, 1960; Beard, 1960, 1962, 1964; Spreiter and Briggs 1962; Spreiter and Hyett, 1963; Mead and Beard, 1964, etc.) had been made using the basically same concept with that of the Chapman and Ferraro theory where the solar wind pressure balances with the magnetic pressure originated from the earth. For the case of the Jovian magnetosphere, however, the internal disc wind essentially controls the structure of the magnetosphere in addition to the intrinsic magnetic field from the planet. The generated planetary disc wind should cease at somewhere near the stational magnetopause. This pause of the planetary wind may essentially be associated with the possible discontinuity, i.e., the shock as has been proposed in the previous paper as “the internal shock” (Aoyama and Oya, 1985), associated with the internal magnetopause (Oya and Aoyama, 1985).

From recent Voyager 1 and 2 observations, significant data of the magnetic field (NESS et al., 1979a, b), the energetic particles and plasma (Krimigis et al., 1979, 1981; Carbary et al., 1981; Scudder et al., 1981) and the plasma waves (Gurnett et al., 1980, 1981; Scarf et al., 1981) were obtained. From the standpoint of the planetary wind in the magnetospheric disc, these data are understood as suggesting the existence of two shocks (the bow shock and the internal shock) and two magnetopauses (the magnetopause and the internal magnetopause).

The present paper is purposed to make theoretical study on the structure and the characteristics of the Jovian magnetospheric boundary region with the calculation of the configuration of the internal shock. We will also present a consistent model of the magnetospheric boundary region. It is also the purpose of the present paper to make comparison of the present model with the data obtained by in-situ observations. In addition to the presentation of the proposal for the large scale structure of the Jovian magnetosphere, the present studies also lead us to an idea that the plasma states surrounding the Jovian magnetosphere can be divided into three components. The first is the magnetosheath plasma that is intimately related to the solar wind plasma; the second is the disc plasma and the third is the magnetospheric lobe plasma. These points are also checked by the data provided by Pioneer and Voyager observations.

2. Theoretical Calculation of the Internal Shock

The location of the internal shock is largely related to the location of the Jovian magnetopause which has theoretically been calculated for the case where the solar wind interacts with the Jovian intrinsic magnetic field under the existence of the internal planetary plasma flow (Aoyama and Oya, 1985). In Fig. 1, the results of the calculated magnetopause are reproduced. Curves showing the locations of the magnetopause at the equator are expressed for the various solar wind dynamic pressure $P_{SW}$. These results in Fig. 1 indicate the clear dawn-dusk asymmetry in the shape of the Jovian magnetopause. The sensitive response of the location to the variation of the solar wind dynamic pressure is also evident suggesting the evidence of “Spongy Nature” of the Jovian magnetosphere observed by Pioneer 10 and 11.
Curves to express the magnetopause (reproduced from AOYAMA and OYA, 1985). Calculations have been made for four cases of the solar wind dynamic pressure $P_{SW}$ where the solar wind is blowing from left to right in the figure. The origin of the coordinate coincides with the location of Jupiter; marks X, O, Y and Z express the locations of the magnetopause crossings observed by Pioneer 10, 11, Voyager 1 and 2, respectively.

(SMITH et al., 1974, 1975) and Voyager 1 and 2 (NESS et al., 1979a, b). Inside the magnetopause, with sufficient distance, the discontinuity called here the internal shock is formed for the interaction process of the super magnetosonic plasma flow with the intrinsic Jovian magnetic field. In order to obtain the location and the extent of the discontinuity we have used the calculated Jovian magnetopause given in Fig. 1 as a boundary frame.

The basic feature of the model is given in Fig. 2 where the solar wind and the planetary wind in the magnetodisc encounter sandwiching the region (hatched area) of the Jovian intrinsic magnetic field. In this hatched area, the magnetic field is compressed by these two plasma winds flowing in counter directions each other (see Section 5 for detailed description of this region). In this theory, we treat the boundary near the equator in the two dimensional case. As has been pointed out by in-situ observations of the Jovian magnetosphere carried out by Pioneer 10, 11, Voyager 1
Fig. 2. Schematic sketch of the boundary structure projected on the equatorial plane for the dayside region of the Jovian magnetodisc associated with the encounter of the super magnetosonic plasma flow in the Jovian magnetodisc with the solar wind. Curves with arrow express the stream lines of the plasma. Labels BS, MP, IMP, IS, SW, MS, IMS, JW and BR are used for Bow Shock, Magnetopause, Internal Magnetopause, Internal Shock, Solar Wind, Magnetosheath, Internal Magnetosheath, Jovian Disc Wind and Boundary Region, respectively. A hatched area shows the pile up region of the Jovian intrinsic magnetic field sandwiched between the magnetopause and the internal magnetopause. A dashed curve in IMS connecting the point $n_1$ on IS to the point $n_2$ on IMP shows the pass of integration in Eq. (9) directed to the normal direction of the stream lines.

and 2, however, the width of the current layer of the Jovian magnetodisc is fairly thick. From our standpoint, the super magnetosonic plasma flows in the Jovian disc region are producing the disc current layer (see OYA and Aoyama, 1985) with certain thickness. The discussing internal shock then has a surface expands in perpendicular direction to the equatorial plane within the thickness of the current layer. The analyses have been made for the location of the internal shock relative to the magnetopause, as has been given in Fig. 3, in which the super magnetosonic wind $V_{JW}$ in region 1 interacts with the internal magnetosheath (region 2) forming the internal shock. Two dimensional shock relations governing the discontinuity are:

$$\rho_1 V_1 = \rho_2 V_2, \quad (1)$$

$$\rho_1 V_1^2 + P_1 + \frac{B_1^2}{2 \mu_0} = \rho_2 V_2^2 + P_2 + \frac{B_2^2}{2 \mu_0}, \quad (2)$$

$$\frac{1}{2} V_1^2 + \frac{\gamma P_1}{\rho_1} + \frac{B_1^2}{\mu_0 \rho_1} = \frac{1}{2} V_2^2 + \frac{\gamma P_2}{\rho_2} + \frac{B_2^2}{\mu_0 \rho_2} \quad (3)$$

and
where $\rho$, $P$, $B$, $\mu_0$ and $\gamma$ are the mass density, plasma static pressure, magnetic flux density, magnetic permeability in vacuum and the ratio of specific heats, respectively; the quantities with subscripts 1 and 2 correspond to the values in region 1 and 2. In the above shock relations $V_1$ and $V_2$ are the normal components of the bulk velocity in regions 1 and 2 across the internal shock surface, respectively. The tangential components of the flow velocity across the shock surface are equal between regions 1 and 2. Equations (1), (2) and (3) describe the conservation laws for the mass, the momentum and energy, respectively. Equation (4) is derived from the equation of the electromagnetic induction for the case of $V \perp B$, under the steady state condition. In regions 1 and 2 near the shock, it is also assumed that the magnetic field keeps constant value in each region. By introducing rates of variables, $\xi$, $\eta$, $M_1$ and $\beta$, as

$$
\begin{align*}
\xi &= \frac{\rho_2}{\rho_1} = \frac{V_1}{V_2} = \frac{B_2}{B_1}, & \eta &= \frac{P_2}{P_1}, & M_1 &= \frac{V_1}{\sqrt{\gamma P_1/\rho_1}}
\end{align*}
$$

and

$$
\beta = \frac{B_1^2/2\mu_0}{P_1}.
$$

We can rewrite the shock relations; i.e., substituting Eq. (5) into Eqs. (2) and (3), it follows that
Thus, from Eqs. (6) and (7), all of the physical quantities in region 2 are related to the physical quantities $V_1$, $\rho_1$, $P_1$ and $B_1$ in region 1 which are obtained from the calculation of the Jovian disc wind.

3. Boundary Condition

For the calculation of the internal shock, it is essential to determine the location of the magnetopause and to have the information of the pressure there as a boundary condition. The location and the shape of the Jovian magnetopause was calculated using the equation of the pressure balance on the surface of the magnetopause, under the assumption that the solar wind plasma and the disc wind plasma interact directly at the magnetopause neglecting the effect of the possible internal shock (Aoyama and Oya, 1985). In the actual case, the internal shock is formed detaching from the magnetopause with a certain distance where the plasma flow which has passed the internal shock decelerated in its speed enters the region of the internal magnetosheath (see Figs. 2 and 3). As has been depicted in Fig. 2, the decelerated plasma continuously flows inside the internal magnetopause. On the surface of the internal magnetopause (IMP), therefore, there exists the balance of the pressure in the perpendicular direction to the internal magnetopause as

$$B_i^2/2\mu_0 + P_i = P_{IS} + B_{IS}^2/2\mu_0$$

where the subscripts I and IS correspond to the values just outside IMP and in the internal magnetosheath (IMS), respectively. When we consider the balance in the wider area covering IMP, IMS and the internal shock (IS) regions (see Fig. 2), the balance is rewritten as

$$B_i^2/2\mu_0 + P_i = P_{IS}(n_{11}) + B_{IS}(n_{11})/2\mu_0 + \int_{n_{21}}^{n_{11}} k_R \rho V^2dn$$

where the $P_{IS}(n_{11})$, $B_{IS}(n_{11})/2\mu_0$, $k_R$, $\rho$ and $V$ are the pressure and the magnetic pressure at point $n_{11}$ on IS, the curvature of the stream line, the density and the flow velocity of the plasma between the point $n_{21}$ on IMP and point $n_{11}$. For this pressure balance, the effect of the plasma flow in IMS is included in the right-hand side terms of Eq. (8). That is, due to the existence of IMP, the plasma flow in IMS changes the flow direction to be parallel to the IMP (see Fig. 2). As has been indicated by Eq. (9), the...
centrifugal force caused by this curved flow gives the pressure gradient in the perpendicular direction of the stream lines. The static pressure related to the flowing plasma in IMS increases with approaching to the IMP (see Appendix for details).

The constancy of the flow energy is kept within the flow tube of the plasma. When we describe the situation more accurately, then, it is required to solve the flow pattern of the plasma flow within the internal magnetosheath. Since the plasma flow in the internal magnetosheath is determined only for the exactly decided internal shock structure, we have no way to find the accurate plasma flow pattern. Instead of solving exact solution, therefore, we use here an approximated plasma flow condition where the plasma in the internal magnetosheath is flowing in parallel with the internal magnetopause. When we select a point Q at a surface of the internal shock, the pressure just outside of the internal shock is related to that at the internal magnetopause (see Fig. 3). Conservation of the total pressure can be achieved in a flow tube where the Bernoulli's law is conserved. For this context, the point P on the internal magnetopause is not located in the same flow tube with the point Q at the internal shock. As has already been discussed here, therefore, we can not directly adopt the pressure at the point P on the internal magnetopause as the pressure at the point Q. To relate the pressure at an arbitrarily selected point to a given point on the internal magnetopause across the flow tube, therefore, we should introduce the adjusting factor $f$. In the present work, we select the point P where the line PQ becomes the normal direction of the internal magnetopause boundary so that PQ becomes the shortest distance between the point Q on the internal shock and the internal magnetopause. There is also the pressure balance between the outer magnetopause and the internal magnetopause. Since Jovian intrinsic magnetic field is sandwiched in the region corresponding to the hatched area in Fig. 3, we can easily use the equation of the pressure balance as

$$B_0^2 / 2 \mu_0 + P_O = B_I^2 / 2 \mu_0 + P_I$$  \hspace{1cm} (10)

where the subscripts O and I express the values just inside and outside, respectively, of the outer magnetopause and the internal magnetopause. Therefore, when we define the pressure $P_3^{\text{total}}$ at the point 3 where is the nearest point from the point Q (see Fig. 3),

$$P_3^{\text{total}} = B_0^2 / 2 \mu_0 + P_O.$$  

In this case we can express, as

$$f \cdot P_3^{\text{total}} = P_2^*$$  \hspace{1cm} (11)

where $P_2^*$ is defined as

$$P_2^* = P_2 + B_2^2 / 2 \mu_0 + \rho_2 V_2^2$$  \hspace{1cm} (12)
where $P_3^{\text{total}}$ expresses the total pressure at the point 3 just inside the outer magnetopause, and $P_2$, $B_2$ and $\rho_2$ are plasma pressure, magnetic flux density and mass density in region 2 just outside the internal shock, respectively. As has been also shown in Fig. 3, the velocity $V$ in Eq. (12) is the component of the velocity $V_2$ in region 2 directed from the point Q to the point 3. Thus, the boundary value $P_2^{*}$ is assumed here to be simply related to $P_3^{\text{total}}$ using the adjusting factor $\gamma$ as has been given in Eq. (11). When we take $\gamma=1$, for example, the expected shock surface merges with the magnetopause. The significant case expected as real situation is then obtained for $\gamma>1$.

In general, the energy density contained in the flowing magnetized plasma changes corresponding to the variation of the flow domain so as to keep the total energy to be constant in the divergence free media for the energy. The plasma in the boundary region sandwiched between the internal magnetopause and the flowing disc wind plasma can suitably be described as three dimensional flows. The relationship controlling the energy flow is expressed as

$$s \rho v \left( \frac{v^2}{2} + \frac{\gamma}{\gamma - 1} \frac{P}{\rho} + \frac{B^2}{\mu_0 \rho} \right) = \text{const.} \tag{13}$$

where $s$ and $v$ are the cross section through which the plasma flows and the flow velocity of the plasma, respectively. It is possible, therefore, that the energy density decreases when the plasma flows into the wider region from the disc wind region passing through the internal shock. The condition $\gamma>1$ is therefore corresponding to the effect of the three dimensional diffusion; i.e., the plasma in the boundary region flows in both longitudinal and latitudinal direction reducing it's energy density.

4. Numerical Results

Using the boundary condition given in the previous section, we can determine the tangential direction of the internal shock surface. Therefore, we are able to trace the location of the internal shock surface numerically. For the calculation of the condition of the pressure balance, we have here defined a function $G(\theta_S)$ for the angle $\theta_S$ which is defined between the tangential direction of the internal shock surface at the point Q (see Fig. 3) and the radial direction whose origin is located at the center of the planet, as

$$G(\theta_S) = P_2^{*} - \gamma P_3^{\text{total}}. \tag{14}$$

The boundary condition is satisfied, then, for $G(\theta_S)=0$. In Fig. 4, calculated results of the function $G(\theta_S)$ are given for six conditions; i.e., $R=84$ R$_J$, 85.8 R$_J$, 86.2 R$_J$, 88 R$_J$, 100 R$_J$ and 102 R$_J$ corresponding to the curves labeled A, B, C, D, E and F, respectively, and the angle $\theta$ is fixed to be $-20^\circ$ for each case, as example cases, in two dimensional polar coordinate system ($R, \theta$) where the origin of the coordinate system is located at the center of Jupiter and the angle $\theta=0$ corresponds to the direction.
Fig. 4. Examples of the value of $G$ (Eq. (14)) as a function of the angle $\theta_S$ at point Q. In the case of curve C where the point Q is located at $R=86.2$ RJ and $\theta=-20^\circ$, there are four solutions labeled 1, 2, 3 and 4 indicated with arrows, that satisfy the boundary condition ($G(\theta_S)=0$). The gap of the solid curve between the solution 1 and the solution 2 corresponds to the condition $M_1<1$. For the case of curve B where the point Q is located at $R=85.8$ RJ and $\theta=-20^\circ$, we can find the solution of the shock surface where two curves corresponding to the solution 3 and 4 are connected smoothly with the angle labeled $\alpha$ (see text).

defined from Jupiter toward the sun. In the calculation of the function $G(\theta_S)$ for these six different locations of point Q, the solar wind condition and the disc wind parameters are fixed and are same as the case of Fig. 6. The number of the solution for $G(\theta_S)=0$ changes depending on the location of the point Q. There are four solutions, at the most, to satisfy $G(\theta_S)=0$ at the point Q as have been indicated by 1, 2, 3 and 4 for the case of the curve C in Fig. 4. The solutions 1 and 2 are obtained under the weak shock condition; i.e., $M_1>1$, while the solutions 3 and 4 are obtained under relatively strong shock condition $M_1>1.5$ again at the point Q.
When four solutions are existing at a given point Q (corresponding to the curve C in Fig. 4), then we can trace back each solution on the equatorial plane starting from the point Q; each curve starting from the point Q corresponds to the possible internal shock surfaces. One example case is given in Fig. 5 where the point Q is selected at $R=86.2\ R_{J}$ and $\theta=-20^\circ$. In this figure, the area inside (Jupiter side) of a dashed line shows a forbidden region for the internal shock surface where no $\theta_{S}$ value is able to exist (corresponding to the case of the curve A in Fig. 4). The solutions correspond to 1 and 4 disappear when the point Q moves outward. This can be understood when we see the change of $G(\theta_{S})$ from the case E to F in Fig. 4 with increasing the distance of the point Q from the planet. The angles corresponding to the solutions 1 and 4 for curve E are indicated by labels 1' and 4' in Fig. 4, because 1' and 4' are continuations of the point 1 and 4, respectively, when $G(\theta_{S})$ changes from the case D to E with increasing the distance. When we trace the curves corresponding to the solutions 2 and 3, in the direction outward from the point Q, the curves suddenly disappear because these solutions change to imaginary at the point Q which is located in between the point Q(C) and Q(D) where Q(C) and Q(D) mean the points whose $G(\theta_{S})$ values correspond to curve C and D, respectively in Fig. 4. When we trace the curves corresponding to the solutions 1 and 2 inward direction, they end at the border of the forbidden region (dashed curve in Fig. 5) corresponding to the transition from the configuration of the curve C to that of the curve B. These solutions discussed above are apparently not the suitable cases to express the internal shock. The suitable solution of the shock surface can therefore be obtained by combination of the solutions 3 and 4 which are traced inward. The solution 3 is valid as internal shock only for the dawn side region, while the solution 4 has its validity only for the dusk side region as has also been indicated in Fig. 5. In Fig. 5, the point Q is selected arbitrarily. This case is, however, not allowed.

![Fig. 5. Possible solutions for the internal shock surfaces passing through the point Q in the two dimensional polar coordinate system ($R$, $\theta$). The location of the point Q is selected where $G(\theta_{S})$ coincides with the case of curve C shown in Fig. 4.](image-url)
as solution possessing the physical meaning because there is no smooth connection between the curve representing solution 3 and that representing solution 4 at the point Q. To obtain the smooth connection of two curves at point Q, therefore, the angle $\theta_{33}$ defined between the radial direction and the tangential direction of the curve 3 and the angle $\theta_{34}$ defined between the radial direction and the tangential direction of the curve
4 should satisfy the condition \( \theta_{31} = \theta_{34} \) corresponding to the point \( \alpha \) on the curve \( B \) in Fig. 4. That is, the equation \( G=0 \) should take the double-root. This situation coincides with the limit for the existence of solution for \( \theta_S \). This means that the point \( Q \) is located on boundary for the existence of the solution. The condition that the equation \( G=0 \) possesses double-root is necessary but not sufficient condition for the existence of the stable shock because there is a possibility that the curves corresponding to the solution are terminated at the boundary of the existence of the solution. The sufficient condition is, therefore, that the double-root \( \theta_S \) coincides with the angle \( \theta_t \) defined between the radial direction and the tangential direction at the given point on the border line.

The internal shock surfaces which satisfy the above conditions are shown in Figs. 6 and 7. For the calculation of the shock surface given in Fig. 6, the following parameters are used: solar wind pressure \( P_{SW} = 0.5 \cdot P_0 \) (for \( P_0 = 5.3 \times 10^{-11} \text{ J/m}^3 \)), the disc wind parameters, i.e., the disc thickness \( D \), initial flux density of disc plasma \( F \), initial electric field \( C* \) and the temperature of the disc plasma \( T \) (see OYA and AOYAMA, 1985; AOYAMA and OYA, 1985), respectively, to be 2, 1, 2 and \( 3.5 \times 10^6 \text{ K} \).

![Fig. 7. Same as Fig. 6 for the case of the small scale magnetosphere.](image-url)
The results given in Fig. 7 are obtained for $P_{SW} = P_0$ with the same parameters for the internal plasma flow. The solution in Fig. 6 correspond to the shock surface for the case of the largely expanded magnetopause located at 115 $R_J$, while the solution in Fig. 7 corresponds to the case of the small scale magnetosphere where the magnetopause is located at 60 $R_J$. The solutions of the internal shock surface are given for two cases corresponding to $f = 1.2$ and 1.5 both for Figs. 6 and 7. In each diagram, the dashed line shows the boundary of the forbidden region for the case where $f = 1.5$, with the dark circle in the center portion which indicates the corotation area limited at 20 $R_J$. The dependency of the shock surface position on the factor $f$ takes place so as to shift the internal shock surface toward the center body (Jupiter) with increasing $f$ value. The resulted shape of the internal shock surface shows the clear dawn-dusk asymmetry corresponding to the dawn-dusk asymmetry of the shape of the given magnetopause. As has been expected by the flow direction of the disc wind (see Fig. 8) and the configuration of the magnetopause (see Fig. 1), the shock strength is also indicating the same tendency of the asymmetry. The strength of the internal shock that is defined by the rates $\xi$ and $\eta$ (see Eqs. (5), (6) and (7)) decreases as the shock surface extends to the dusk side tail and the shock surface is ceased at the point $M_1 = 1$. Though the internal shock expanded in the dawn side is stronger than that in the dusk side, there is also the end point of the internal shock in the dawn side corresponding to

![Stream lines (solid lines) of the Jovian disc wind. The dashed circles show the radial distance from Jupiter. A dark circle in the center portion expresses the corotation region of the plasma (see OYA and AOYAMA, 1985 for calculation).](image)
the change of the configuration of $G(\theta_s)$ from the type of curve E to F shown in Fig. 4. In Fig. 8, an example of the stream lines of the Jovian disc wind is indicated. The Jovian disc wind has larger azimuthal velocity component (corotation direction) when we make observation in a region closer to Jupiter. Therefore, there may be a limit for the existence of the internal shock for the case of a very small magnetosphere.

5. Model of the Boundary Structure in Low Latitude Magnetospheric Boundary Region

As has been studied already in the previous paper (Oya and Aoyama, 1985), there is a super magnetosonic plasma flow called Jovian disc wind in the low latitude region of the Jovian magnetodisc. Jovian magnetosphere is essentially interacting with the solar wind plasma that is also flowing with super magnetosonic speed. There should be, therefore, interaction region of these two super magnetosonic flows at the Jovian magnetospheric boundary. For consideration of these interaction processes, we have depicted the model in Fig. 9 where the interaction region is indicated with a

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Fig. 9. Schematic sketch of the Jovian magnetosphere and its environs in equatorial plane. A dotted region shows a boundary region sandwiched between the solar wind and the Jovian disc wind that is blowing in equatorial plane. A meshed circle at the center of the figure expresses a corotation region. Solid lines with arrow show the stream lines of the solar wind and the disc wind.
bow shape band as pointed out with dotted area. The interaction region should be
associated with two edges; the outer edge is generated by virtue of the interaction with
the solar wind and the inner edge is formed by virtue of the interaction with the disc
wind.

These two edges are also associated with two remarkable transient layers, the
first is the shock and the second is the magnetopause. On these theoretical bases, we
propose a unique structure of the Jovian magnetospheric boundary containing seven
different regions as shown in Fig. 10, such as 1) Solar wind plasma, 2) Magnetosheath
(Region I), 3) Boundary layer (Region II), 4) Pile up magnetic field (Region III), 5)
Internal boundary layer (Region IV), 6) Internal magnetosheath (Region V) and 7)
Disc wind plasma. Among these seven regions, region III is a unique area in the sense
that no analogous region is existing in the earth's magnetosphere. The magnetic field
in the disc region is frozen in the disc plasma flow and is compressed against the
internal magnetopause near the end of the radial flow of the wind. Therefore, the pile
up region of the Jovian intrinsic magnetic field is formed between two magneto-
pauses. Due to intense magnetic field near the internal magnetopause the plasma is
essentially bothered to enter the pile up region of the magnetic field. Furthermore, the
high energy plasma with tenuous density in this pile up region (region III) can easily
escape along the magnetic field towards high latitude region; the number density of
the plasma is then maintained in fairly low level. The boundary between region IV and
V is called internal magnetopause as has been already introduced by OYA and
AOYAMA (1985). Considering physical properties of these characterized regions II
and IV, at present, we defined these transient regions from region I to region III and
from region V to region III as boundary layers.

For the case of the earth's magnetosphere, it is found through many observations
(RUSSELL and ELPHIC, 1978; RUSSELL and GREENSTADT, 1979; PASCHMANN et al.,
1978; PARKS et al., 1978; EASTMAN and HONES, 1979; BERCHEN and RUSSELL, 1982;
etc.) that the bow shock, the magnetosheath, the magnetopause, the boundary layer
and the magnetosphere mantle are existing. Due to limitation of the data, however,
we could not definitely conclude the characteristics for these transient regions such as
regions II and IV, whether the regions are similar to the earth's magnetospheric
boundary layer or not.

To examine the validity of the proposed model, we have used the data obtained in
the inbound passes of Voyager 1 and 2 spacecraft which passed through the dayside
magnetospheric boundary region where the present theoretical model can be seen
more clearly.

The upper panel of Fig. 11 shows data of the observed total intensity of the
magnetic field with the index of the perturbation (RMS) of the magnetic field for the
observation of the Voyager 2 inbound pass (NESS et al., 1979b). A dotted region (from
63 R_J to 41 R_J) in this figure expresses the boundary region where regions II, III, IV
and V given in Fig. 10 are included. The lower panel shows the solar wind pressure at
the Voyager 2 spacecraft predicted on the basis of the solar wind data detected at
Voyager 1 (BRIDGE et al., 1979b). When the Voyager 2 spacecraft was in the boundary
region the solar wind pressure was relatively low and steady. Therefore, we are able to
Fig. 10. A model of boundary structure of the Jovian magnetosphere as a meridional cross section near the equatorial region. A spatial extent of each region separated by vertical lines is given arbitrarily.
Fig. 11. Upper panel: Magnetic field intensity ($B$) and Pythagorean mean RMS deviation (16-minute averaging intervals) for inbound pass. Crossing times of the bow shock and the magnetopause with the spacecraft are indicated by BS and MP, respectively. $R_J$ refers to Voyager 2's planetocentric distance at the beginning of each even-numbered day (after Ness et al., 1979b). Lower panel: The solar wind pressure at the position of Voyager 2 predicted on the basis of solar wind data measured at Voyager 1. CA is the time of closest approach to Jupiter in the frame of the spacecraft event time at Voyager 2. The pressure is in units of $10^{-10}$ dyne/cm$^2$ (after Bridge et al., 1979b).
understand that the dotted region in the upper panel is indicating the spatial extent rather than the time dependent feature. In Fig. 12, the count rate of the energetic particles (in middle and bottom panels (KRIMIGIS et al., 1979)) are indicated also with the data of the magnetic field intensity (top panel). In Fig. 12, correspondency of theoretically predicted regions, as given in Fig. 10, is indicated on the observational data obtained by Voyager 2 with the roman numerals. It is clear that a principal feature of the observed magnetic field intensity, inner side of the boundary region, indicates the persistence of 10 hour periodicity with the occurrence of two dips in the field intensity associated with the increase of the perturbation of the magnetic field (RMS); and this tips correspond to the disc crossings of the spacecraft. At about 41 R\(_J\) from the planet, the flowing disc plasma encounters the weak internal shock where the magnetic field in the disc region that corresponds to the minimum value of the data turns to high level in the region of the internal magnetosheath (region V). The jump of the magnetic field intensity at about 41 R\(_J\) suggests the existence of the MHD shock wave there. In the region of the internal magnetosheath, the disc structure becomes weaker but there still exists the sign of the 10 hour periodicity because of the existing of the flowing plasma in the internal magnetosheath. In the outer region of the internal magnetosheath, there is the pile up region of the magnetic field corresponding to regions II, III and IV, though the extent of region IV cannot be identified clearly. In this area, the magnetic field shows highly perturbed state with no periodicity.

The boundary structure discussed for the magnetic field data corresponds closely to that indicated by the observed profiles of the count rate of the energetic particles shown in the middle panel. The periodicity of the count rate profiles is also very similar to that of the magnetic field data, though the count rate maxima correspond to the minima of the magnetic field strength. In the bottom panel of Fig. 12, the ratio of the count rate of the protons to that of the alpha particles is indicated; it is remarkable that the ratio is positively correlated to the magnetic field intensity. In the solar wind, we can find a given amount of the ratio which comes from the solar atmosphere that is close to the cosmic abundance. The magnetic field of the planet acts as a barrier of the solar wind particles and a guide of the particles from the planet. Therefore, we can see a high ratio of the count rate of the protons to that of the alpha particles in the lobe as well as the pile up region of the planetary magnetic field. The lower value of the ratio in the disc plasma than that in the lobe is, then, considered to be some hidden effects of the origin of the disc plasma. The detailed studies on this mechanism is remained for future. On the base of the data of the protons to alpha particles ratio, we can investigate the differences of the two magnetosheaths in regions I and V from the pile up region of the magnetic field (region III).

Figure 13 shows the data obtained in the inbound pass of the Voyager 1 spacecraft. The upper panel expresses the magnetic field data (NESS et al., 1979a); and the plasma density profile (BRIDGE et al., 1979a) is shown in the lower panel. The minimum values of the magnetic field intensity are shown with increasing the plasma density indicating the passage of the spacecraft through the current sheet of the disc. Though it is difficult to identify the fine structure of the boundary region using the magnetic field data because of data gaps, we can divide the boundary region
Fig. 12. Top panel: Same as the upper panel of Fig. 11 (after Ness et al., 1979b). Middle panel: Profiles of the count rate of energetic particles measured along the inbound pass for 15-minute averages. Boundaries labeled BS (bow shock) and PB (plasma boundary) have been determined from the LECP anisotropy and rate data. Bottom panel: The ratios of the proton to alpha particle are shown also for identifying the boundaries (after Krimigis et al., 1979).
Fig. 13. Upper panel: The magnitude and Pythagorean mean rms deviation of the magnetic field observed in Voyager 1 inbound pass. BS (bow shock) and MP (magnetopause) are indicating the crossing times of the corresponding regions by Voyager 1 spacecraft (after Ness et al., 1979a). Lower panel: Positive ion density observed during the Voyager 1 inbound pass, in number per cubic centimeter. Vertical arrows indicate crossing points of the magnetic equator for Voyager 1. A dotted region shows the boundary region discussed in the present paper (after Bridge et al., 1979a).
Structure of the Jovian Magnetospheric Boundary Region

(described by a dotted area) into regions II, III, IV and V using the plasma density data. The inner edge of the boundary region where the plasma density at the disc (characterized by maxima of the profile) changes to high level, may correspond to the very weak internal shock.

To obtain more direct evidence for existence of the internal shock, data of flow directions and speeds of the disc plasma, from the low-energy charged particle detector on board the Voyager 1 and 2 spacecraft are used. Upper and lower panels of Figs. 14(a) and 15 show the direction and speed of flowing plasma, respectively (reproduced from Figs. 18 and 19 in the paper by CARBARY et al., 1981). We have decided a large excursion of the flow direction of the plasma and sudden change of the plasma flow speed observed in the region corresponding to a hatched portion in Fig. 14(a) (indicated between two panels to show the coincidence of sudden change of the flow direction and the sudden change of the speed) are the manifestation of the existing internal shock. This hatched region has also been obtained from the results given in Fig. 12. To obtain variations of the direction and the speed of the plasma flow, the observed values are indicated for the running average for seven data points as given in Fig. 14(b) corresponding to data plotted in Fig. 14(a). Arrows in the lower panels of Figs. 14(a) and (b) indicate the location of the internal shock. The large change of the flow direction may suggest the existence of the turbulent region around 40 to 44 RJ near the internal shock. The data of the flow direction also show that there exist two characteristic regions sandwiching the turbulent region associated with the internal shock; i.e., in the region inside of the internal shock around 37 to 40 RJ, where the average flow direction shows the lower angle than that of the corotation direction suggesting the existence of the theoretically predicted disc wind. In the outer region of the internal shock from 44 to 50 RJ, the average flow direction is nearly equal to the corotation angle. This difference of the average flow directions is consistent with the change of the direction predicted from the MHD shock theory suggesting the existence of the internal shock.

Observation results of the Voyager 1 spacecraft are shown in Fig. 15 in the same format as Fig. 14(a). A possible location of the inner most boundary layer that may be corresponding to the internal shock is again indicated by a hatched region in Fig. 15. In this region, however, we cannot find clear evidence of the internal shock such as abrupt changes of the flow speed and the flow direction. In the case of Voyager 1 encounter with Jupiter, the magnetosphere was largely compressed by the strong solar wind pressure. Under this condition, therefore, it is considered that the development of the super magnetosonic wind was not resulted; and the disc plasma flow took place under the sub-magnetosonic breeze condition (see OYA and AOYAMA, 1985 for details). The results given in the lower panel of Fig. 15 are consistently indicating the existence of the sub-magnetosonic breeze; i.e., the flow speed inside the hatched region is always lower than the local corotation speed.

The schematic sketch of the boundary structure of the low latitude Jovian magnetosphere obtained as a result of the data analysis for the inbound passes of Voyager 1 and 2, is then finally expressed as given in Fig. 16. The boundaries between regions II and III and regions III and IV are basically not so clear because these
regions (regions II and IV) are transient layers associated with region III where the magnetic field from the planet is piled up with few plasma.

6. Confirmation of the Disc Region

Comparison of the data obtained by inbound and outbound passes of the Pioneer 11 spacecraft provides us with other confirmation of the boundary structure in low latitude region of the Jovian magnetosphere. Figure 17 shows the variance data of the ULF wave components obtained by Pioneer 11 inbound pass; Figure 18 also shows the same kinds of data for the case of outbound pass of Pioneer 11 (Kivelson and Rosenberg, 1976). When Pioneer 11 was passing through the boundary region of the Jovian magnetosphere in both inbound and outbound passes, the solar wind pressure at Pioneer 11, predicted on the basis of the solar wind data at Pioneer 10
Fig. 14(b). The running average for seven data points of the flow direction (upper panel) and the flow speed (lower panel), in the region near the internal shock, based on the data in Fig. 14(a).

(SMITH et al., 1978), was relatively steady. Therefore, variations of the data obtained in the boundary region should be understood as results of the spatial structure.

Figure 17 shows the total variances of the ULF waves in the top two panels and the histograms of the ratio of the parallel component of the ULF waves with respect to the main magnetic field to the total variances in the bottom two panels for two frequency bands (KIVELSON and ROSENBERG, 1976). We can see from the data in the top panels that the power of the ULF waves is dominated on the boundary regions corresponding to regions II, III, IV and V except for the wave component, by virtue of field aligned currents, that is expressed by the spectrum labeled $F$. The intensity of the waves in the boundary region is larger than that of the magnetosheath (region I). This evidence suggests that the source of the field fluctuations is not the result of the waves
Fig. 15. Same as Fig. 14 for the inbound leg of the Voyager I encounter data (after CARBARY et al., 1981).
The speeds represented by the solid circles in the lower panel are published values of BELCHER et al., 1980, while the lines inside the 20 R_J are limits taken from MCNUTT et al., 1979. A hatched region connecting two panels indicates the possible range of the position of the innermost discontinuity obtained from parameter changes in Fig. 13.

Fig. 16. Schematic illustration of the meridional cross section for the boundary structure of the low latitude Jovian magnetosphere. The solid lines show the magnetic field lines; in a dotted area, the magnetic field from the high latitude magnetosphere is piled up being sandwiched between the solar wind and the disc wind.
transported from the magnetosheath through the magnetopause, but from the internal origin. Using the ratio of the parallel to the total variance described in bottom two panels, we are able to indicate the internal structure of the boundary region (regions II, III, IV and V) as follows. An abrupt drop in the power of the parallel component of the ULF variations inside of 45 R\textsubscript{J} conceivably indicates the internal shock as crossing the innermost boundary of the turbulent boundary region. In regions I and II before entering the magnetopause and regions IV and V before arriving at the internal shock, the ULF wave spectra are characterized by the enhancement of the parallel component of the MHD waves compared with the other regions where the power of the ULF waves of the transverse component is dominated. This is a reflection of the evidence that in these two regions, the existence of the hot plasma significantly affects on the balance instead of the magnetic field with high energetic particles as the cases in the lobe and the piled up magnetic field region (region III). The enhancements of the power of the parallel component of ULF waves in these two regions also suggest the existence of the turbulent regions formed in the downstream side of the shock waves (both in the internal shock and the bow shock).

The boundary region described in Fig. 18 (Kivelson and Rosenberg, 1976) for the case of the outbound pass of Pioneer 11 is characterized by the narrowness of the spatial extent of the boundary regions though there is a wide range of the variation due to the time dependent fluctuation of the magnetopause position. The top two panels of Fig. 18 show the variance of the ULF wave whose occurrence is confined to the narrow region in the neighbourhood of the magnetopause and the intensity is smaller than that of the inbound pass. In the bottom two panels that show the ratio of the parallel component of the power of the waves to that of the total variances, it is also difficult to identify the clear internal structure for the boundary region as described for the case of the inbound observation given in Fig. 17. The narrowness of the magnetopause and associated boundary regions where we can not find any clear internal structure, that was detected by the outbound pass observations of the Pioneer 11 spacecraft, can be concluded as the characteristics of the magnetopause boundary in the region of high magnetic latitude where no plasma disc is existing. Due to the lack of the internal plasma flow, the structure of the magnetopause becomes very similar to that of the earth's magnetosphere, in this high latitude region.

We summarize the results of the data analyses in Table 1 for Voyager 1, 2 and Pioneer 11 spacecraft. The boundary region corresponding to the perturbation region of the magnetic field is found for all of the passes. In three low latitude passes except for Pioneer 11 outbound pass, there are widely extended boundary regions (about 20 R\textsubscript{J} in radial distance along the satellite passes). Furthermore, we can find the signs of the existence of the internal structure of the boundary region, that is, the internal shock as a innermost boundary of the boundary region and the internal magnetopause that separates the internal magnetosheath (region V) from the pile up region of the magnetic field (region III). We cannot find a clear evidence of the internal shock in the case of the inbound pass of Voyager 1 among three low latitude passes because the magnetosphere was largely compressed by the solar wind and, therefore, the super magnetosonic disc wind was not generated. In contrast with the observation results of
7. Conclusion

The theoretical study based on the numerical calculation has been carried out for the internal shock that is formed as a MHD shock due to the encounter of the solar wind with the super magnetosonic Jovian disc wind in the Jovian magnetospheric disc region. The boundary associated with the shock situation have been calculated based
Fig. 18. Same as Fig. 17 for the data observed in the outbound pass of Pioneer 11 (after Kivelson and Rosenberg, 1976).

Table 1. Comparison of boundary layer crossing for four cases. “Yes” and “No” in corresponding lines and columns show, respectively, that there were “existing” and “not existing” the boundaries or discontinuities for the considerations.

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Pioneer 11</th>
<th>Pioneer 11</th>
<th>Voyager 1</th>
<th>Voyager 2</th>
</tr>
</thead>
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<td>Outbound</td>
<td>Inbound</td>
<td>Inbound</td>
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<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Local Time</td>
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<td>11:00</td>
<td>10:30</td>
</tr>
<tr>
<td>Boundary Region</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
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<td>7 RJ</td>
<td>17 RJ</td>
<td>22 RJ</td>
</tr>
<tr>
<td>Structure</td>
<td>Internal Shock</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Internal Magnetopause</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
on the balance of pressure of the solar wind with the Jovian intrinsic magnetic field which is piled up by the internal planetary wind (Aoyama and Oya, 1985).

A new evidence on the process of the theoretical studies has been obtained, that is, the three dimensional diffusion of the energy density of the magnetized plasma in the internal magnetosheath is important to provide the conditions observed by Voyager spacecrafts. We therefore introduced the pressure adjusting factor $f$ to select the boundary condition as the variation effect of the energy density contained in the flowing plasma. The $f$ value is usually set between 1.2 and 1.5.

The local solution that satisfies the shock condition is not uniquely defined. When we consider the response of the internal shock surface for time dependent variation of the pressure surrounding the internal shock, however, the most stable solution can be uniquely selected. This stable solution is characterized with the smooth connection of the different branch of solutions. The obtained shock surfaces indicate an asymmetrical characteristics; that is, the internal shock is stronger in the dawn side than in the dusk side of the Jovian magnetodisc. The dusk side shock which is weaker than that in the dawn side has a tendency to disappear at the intermediate position where $M_1 = 1$.

The internal shock is formed by the super magnetosonic wind in the dayside and dusk side region (except for the midnight region) of the Jovian magnetodisc in the same way as the case of the bow shock generated by the solar wind. The intrinsic magnetic field from the planet is sandwiched between the solar wind and the internal disc wind. Centered around this sandwiched magnetic field region, that is called pile up region of the magnetic field, we have proposed the existence of the boundary layers in the side of magnetosheath and also in the side of the Jovian disc wind. The possible regions and boundaries associated with the magnetopause are summarized sequentially from the solar wind side to the disc wind side as, I) Magnetosheath, II) Boundary layer, III) Pile up region of the magnetic field, IV) Internal boundary layer and V) Internal magnetosheath. Between these regions there are remarkable boundaries as i) Bow shock that exists between the solar wind plasma and the magnetosheath plasma, ii) Internal shock that exists between the disc wind plasma and the internal magnetosheath plasma. The boundary layer and the internal boundary layer are included in different concepts using the terminologies as the magnetopause and the internal magnetopause, respectively.

All these concepts are checked based on the Voyager 1, 2 and Pioneer 11 observation data. For the steady condition of the solar wind, we can find confirmation about the existence of expanded boundary regions having the internal structure, except for the outbound case of the Pioneer 11 observations that were carried out in the region of the high magnetic latitude where we cannot expect the existence of the plasma disc nor the planetary wind. In this high latitude case, the data are consistent with the earth's magnetospheric boundary. The evidences of the internal shock have been checked using data provided by the Voyager 1 and 2 observations. It is inferred that conditions are not necessarily in favor for the formation of the internal shock in the case of the Voyager encounters because the Jovian magnetosphere had been largely compressed due to the high solar wind
activities. Nevertheless, we can find the signs suggesting the existence of the internal shock in the data of Voyager 2 inbound trajectory, while no clear evidence of the internal shock has been identified for the case of Voyager 1 inbound trajectory. In the case of Voyager 1 encounter, the magnetosphere was more compressed than the case of Voyager 2 encounter.

We didn’t use the data obtained by Pioneer 10 inbound pass, because we could not see the development of the magnetodisc in this trajectory. The cause of the lack of the disc formation can be attributed to the changeable solar wind condition that disturbs the development of the plasma disc and also indicates very violent change of the magnetopause location. Fast change of the solar wind pressure may be superposed on the development of the convection motion of the disc plasma. Therefore, in a certain range, the partially flowing planetary wind may be interrupted. The macroscopic control of the planetary wind due to changing solar wind pressure is, however, not investigated in the present paper yet and remains for future studies.

APPENDIX

The decelerated plasma flow through the internal shock approaches to the internal magnetopause changing its flow direction towards the direction parallel to the boundary of the internal magnetopause (see Fig. A-1). The flowing plasma in the internal magnetosheath is controlled by the equation of motion as

![Fig. A-1. Plasma flow in the internal magnetosheath (IMS) and coordinate system. The plasma flowing outwards changes the direction after passing through the internal shock (IS) due to the existence of the internal magnetopause (IMP). The unit vectors $\mathbf{t}$ and $\mathbf{n}$ are defined in parallel and orthogonal directions to the stream line, respectively. The points $n_1$ and $n_2$, respectively, on IS and IMP are same as the case of Fig. 2 in text.](image-url)
for steady state condition where \( v, \rho, P_{IS} \) and \( \Omega \) are the velocity, the mass density, the static pressure of the plasma and the potential of external force, \( B_{IS}^2 / 2 \mu_0 \), respectively. Using a curvilinear coordinate system indicated in Fig. A-1, the left hand side term of Eq. (A-1) is rewritten as

\[
(v \cdot \text{grad})v = -\frac{1}{\rho} \text{grad}(P_{IS} + \Omega),
\]

\( (A-1) \)

Using a curvilinear coordinate system indicated in Fig. A-1, the left hand side term of Eq. (A-1) is rewritten as

\[
(v \cdot \text{grad})v = V \frac{\partial V}{\partial s} t + V^2 k_R n,
\]

\( (A-2) \)

\[ v = V t \]

and

\[ \frac{\partial t}{\partial s} = k_R n, \]

where \( s, t, n, k_R \) and \( V \) are the distance along the stream line, the unit vectors in the tangential and normal directions of the stream line, the curvature of the stream line and the velocity of the plasma, respectively. The equation (A-1) is, therefore, rewritten as

\[
\text{grad}(P_{IS} + \Omega) = -\frac{1}{2 \rho} \frac{\partial V^2}{\partial s} t - k_R \rho V^2 n.
\]

\( (A-3) \)

The normal component of Eq. (A-3) is given by

\[ \frac{\partial}{\partial n} (P_{IS} + \Omega) = -k_R \rho V^2. \]

\( (A-4) \)

From Eq. (A-4) we can understand that the centrifugal force caused by the curved flow generates the gradient of the static pressure. The difference of the static pressure between point \( n_1 \) on the internal shock and point \( n_2 \) on the internal magnetopause (see Fig. A-1) is obtained by integrating the Eq. (A-4) from \( n_2 \) to \( n_1 \) in the direction perpendicular to the stream line. That is,

\[ (P_{IS} + \Omega)_{n_1} - (P_{IS} + \Omega)_{n_2} = \int_{n_2}^{n_1} k_R \rho V^2 dn, \]

\( (A-5) \)

where subscripts \( n_2 \) and \( n_1 \) in the left hand side mean the values at the corresponding points \( n_2 \) and \( n_1 \). By this effect, the streaming plasma in the internal magnetosheath contributes to the pressure balance near the internal magnetopause where the plasma flows almost in a parallel direction to the surface of internal magnetopause. The balance equation in text, Eq. (8), therefore can be rewritten as
\[ B_1^2/2\mu_0 + P_t = P_{Is}(n_1) + B_{Is}^2(n_1)/2\mu_0 + \int_{n_1}^{n}\kappa_R \rho V^2 d\mu. \]  

(A-6)

where

\[ P_{Is}(n_1) \equiv (P_{Is})_n. \]

and

\[ B_{Is}^2(n_1)/2\mu_0 \equiv (\Omega)_n. \]

REFERENCES


