

INSTITUTE OF PLASMA PHYSICS

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# RESEARCH REPORT

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Interaction of Solar Plasma Streams with the  
Outer Geomagnetic Field

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## Abstract

The general nature of the magnetic field surrounding the earth is discussed using various measurements made by space probes since 1958. It is shown that the outer geomagnetic field consists of two regions: the standing shock layer and the geomagnetic cavity. The pattern of these regions in the equatorial plane is shown in the frame fixed to the sun. The shock layer, in which turbulent fluctuations of magnetic field are characteristic, appears beyond 10 earth's radii in the sunward side even in a geomagnetically quiet period. The shape of the shock front ( the boundary to a quiescent interplanetary plasma ) is approximated as a hyperbola, with a stand-off distance of the order of 5 earth's radii. This standing shock layer is terminated by the geomagnetic field cavity inside, being a spherical shape in the day-side and an elongated tail in the night-side. It is also noted that the axis of symmetry of this pattern seems to be tilted somewhat towards west of the sun.

The ordinary shock theory of a continuous flow is applied, assuming that the interacting plasma is magnetized so that the mean free path may be replaced by the Larmor radius of the medium. The theoretical estimations of the shock position and the size of the geomagnetic cavity are then compared with the observed ones. It is found that the observed shock wave is consistent for a supersonic flow of Mach number 2-5. The estimated values of a typical quiescent solar plasma stream are  $U = 400 - 500 \text{ km/s}$ ,  $n = 5 / \text{cm}^3$  and  $B = 10 \text{ gamma}$ .

## 1. Introduction

In recent years, a growing interest has arisen about the fringe region of the terrestrial magnetosphere where interplanetary gas interacts with the outer geomagnetic field. Several deep space probes have successfully measured the nature of existing plasma and magnetic field, and a further discussion on the results of exploration is now one of the prime subjects of interplanetary physics.

It has been revealed that the strength of the geomagnetic field decreases with distance from the earth as the inverse-cube law. This relation is generally hold up to the distance of about several earth's radii (abbreviated by  $a$ ), which may be termed as the inner magnetosphere. However, with increasing distance, the strength of field becomes to exceed over the predicted value in the outer magnetosphere; though it still decreases steadily (Coleman 1962). This extended geomagnetic field changes suddenly near a distance of  $10a$ , according to the observation made by Explorer XII (Cahill and Amazeen, 1962). The field transition across the boundary is remarkable ; an abrupt change of the polarity and the field strength occurs within a distance of a few hundred kilometers. Beyond this limit, turbulent magnetic fields are characteristic, which extend and then submerge gradually into rather quiescent interplanetary field. Such a transient region of turbulent magnetic fields, which would be called the magnetopause, was also encountered by Pioneer I (Sonett 1962, 1963) and Pioneer V (Coleman 1962) at some distances between  $10 \sim 25a$ . The Explorer X measurement indicated the existence of similar transition at distances beyond  $23a$  for its orbit towards the night-side of the earth (Heppner et al 1962). It should be noted that this boundary of the geomagnetic field is coincident with the outer limit of the radiation belt of trapped energetic particles (Rosser et al 1962). Localized region of less energetic particles of a few hundred electron-volts have been detected occassionally beyond this limit by Pioneer IV (Van Allen and Frank 1959),

Lunik I, II (Gringauz 1961) and Explorer X (Bridge et al 1962).

Thus, the environment of the geomagnetic field is characterized by three regions, viz., the inner and outer-magnetosphere, and the magnetopause surrounded by interplanetary space. A schematic representation of this is illustrated in Fig.1, which is mainly based on the Explorer XII results. It is generally believed that the enhanced magnetic field in the outer magnetosphere is caused by the effect of compression due to the surrounding interplanetary gas pressure. An interpretation offered to the boundary region of the geomagnetic cavity is of considerable interest. Axford (1962) and Kellogg (1962) have suggested that the turbulent magnetopause outside of the geomagnetic cavity may be identified as the hydromagnetic shock layer produced by solar streams flowing past the earth. The idea of impacting supersonic plasma is a new approach to the old Chapman-Ferraro's problem for the geomagnetic cavity formation, and a further study will provide not only a better understanding of the mechanism but also important knowledge on the existing interplanetary plasma.

In this report, nature of the outer geomagnetic field is re-examined, using all available results of space probes. The general pattern of the geomagnetic field and its environment will, then, be interpreted with a simple dynamical theory of supersonic fluid, taking into account the hydromagnetic nature of interplanetary medium. Some implication of the present result is also discussed briefly.

## 2. Flow pattern and shape of the geomagnetic cavity

All published results on space probe measurements since 1958 have been examined. A comprehensive survey of magnetic field measurements by Coleman (1962) and detailed descriptions on Explorer X and XII are available. From these data, the relevant information is summarized in Table.1, in which the orbital elements and geomagnetic activity during 24

hours period after launching of space probes are included. The positions of the boundaries of the inner and outer magnetosphere ( $r_1$ ) and of the magnetopause ( $r_2$  and  $r_3$ ) are estimated, which are based on the definition mentioned earlier.

Although no magnetic data were available for Pioneer III, IV, Lunik II, III and Venus IV, some of them have been judged from the result of plasma measurements.

Since most space probes traversed the region near the earth's equatorial plane, their orbits are projected on the equatorial plane with the frame fixed to the direction of the sun. As shown in Fig.2, the estimated location of the magnetopause, in which turbulent magnetic fields are characteristic, is indicated by a massive line along their orbits, and also the position of the inner magnetosphere boundary by a dot. Distances from the center of the earth are measured in the unit of the earth's radius.

It is evident that the shape of the magnetosphere (geomagnetic cavity), is hemispherical with a radius of about  $10a$  in the day-side, and an elongated tail is formed in the night-side. This is in accordance with the theoretical prediction made by several investigators in the past few years (Ferraro 1960, Piddington 1960, Johnson 1960, Beard 1960, Dungey 1961, Slutz 1962, Spreiter and Briggs 1962, Harrison 1962, and Parker 1962). The region of fluctuating magnetic fields appears beyond this cavity. The frontal surface, the boundary to quiescent interplanetary field, is situated at distance of  $4 - 5a$  ahead of the cavity in the day-side, and its shape is nearly hyperbolic with the axis of symmetry being tilted about  $15^\circ$  or somewhat more towards west of the sun-earth line. Another important remark on the present result is that the existence of such turbulent magnetopause is a quasi-permanent feature, being observable even in a geomagnetically very quiet period. This is well recognized for the evidences obtained by Pioneer I, Explorer X and XII.

The recent interplanetary probe, Mariner II, provided further new and valuable information concerning the nature of interplanetary medium. The observation reveals the continual outward streaming of solar plasma with the density of about 5 particles/cm<sup>3</sup> and the velocity of 400 -600 km/sec, though they vary rather wide range (Neugebauer and Snyder 1962). The plasma is permeated by magnetic field of 5 ~ 10 gamma (  $1 \gamma = 10^{-5}$  gauss ), which lies mainly in the ecliptic plane (Coleman et al 1962).

### 3. Interaction of solar plasma streams with the geomagnetic field

The problem of an interaction between the geomagnetic field and solar streams is certainly very old, initiated by Chapman and Ferraro in 1930. However, it is rather recent years that the nature of interplanetary plasmas becomes apparent by the direct space probe measurements. Meanwhile, though the inherited basic idea is still valid, the present understanding of this problem is gradually changing because of the realization of interplanetary space filled with plasmas permeated by weak magnetic field. The magnetic field, despite its weakness, has important effect and the physical nature occurring there is essentially hydromagnetic ; i.e., any pressure disturbance propagates with the velocity of Alfvén wave. Since this characteristic speed is much slower than the bulk speed of a solar stream, which is of the order of 500 km/sec, the impact of solar plasma streams against the geomagnetic field is supersonic in the hydrodynamic sense (Gold 1962). An important consequence of this situation is the appearance of a standing bow shock wave in front of an obstacle such as the geomagnetic cavity, which has been suggested by Axford (1962) and Kellogg (1962).

Although such hydromagnetic shock wave is of the collision-free type, the ordinary shock theory of a continuous flow may be applicable, provided that a solar plasma stream is embedded by weak magnetic field so as to

replace the mean free path by the ion gyro-radius, which is considerably small compared with the scale of relevant length (Harrison 1962). Then, the static pressure in the plasma must be the sum of kinetic and magnetic terms,

$$p = 2 n k T + \frac{h^2}{8 \pi} \dots\dots\dots(1)$$

where  $n$ ,  $T$  and  $h$  are the number of density of ions or electrons, temperature and magnetic field, respectively. The magnetic (Alfvén) Mach number is defined for the flow speed  $U$ ,

$$M = U / \sqrt{\frac{\gamma p}{\rho}} \dots\dots\dots(2)$$

where  $\rho = nm$ , and  $\gamma = 2$  is taken for an ionized gas.

An exact treatment of a solar plasma impacting at a supersonic speed against the geomagnetic field is extremely complex. However, for a crude approximation the shape of a shock front is given by the ordinary shock theory. Namely, referring the geometry shown in Fig.3 with conventional hydrodynamic notations, the distance to a shock front is expressed by

$$\frac{r}{r_s} = \frac{1 + \sec \beta}{1 + \sec \beta \cos \phi} \dots\dots\dots(3)$$

and

$$\sin \beta = 1/M_1 \dots\dots\dots(4)$$

$\beta$  is the Mach angle for an unshocked flow  $M_1$ , and the curve is assumed as a hyperbola asymptotic to the Mach line.  $r_s$  is the distance of the normal shock front, and is given approximately by

$$r_s = r_* \sec \beta \dots\dots\dots(5)$$

$r_*$  corresponds the distance for a hypothetical flow of  $M_1 = \infty$ . According to the formulas derived by Hida (1953) for the shock produced by a spherical obstacle of the radius  $r_0$ ,  $r_* = 1.24 r_0$  for the case of  $\gamma = 2$ .



An approximate gross shape of the geomagnetic cavity is obtained by a simple consideration that the geomagnetic field is compressed on the day-side by the momentum flux and on the night-side by the hydrostatic pressure of the stream. The size of frontal cavity  $r_0$  is obtained by equating the pressure at the stagnation point  $p_0$  and the geomagnetic field pressure inside the cavity surface. Then,

$$r_0 = a \left[ \frac{(2 f B_0)^2}{8 \pi} / p_0 \right]^{1/6} \dots\dots\dots (6)$$

in which  $B_0 = 0.31$  gauss and  $f$  is a constant, being variable between  $\frac{3}{2}$ , for a spherical surface, and 1, for a flat surface approximation. The equatorial distance at  $\phi = \pi/2$  is given by (Harrison 1962)

$$r_1 = r_0 \left( \frac{3 \pi}{4} \right)^{1/3} \dots\dots\dots (7)$$

The distance of the tail-end is estimated by assuming that the boundary layer is virtually a free surface which is affected only by the static pressure well behind the shock front,

$$r_t = r_1 \frac{U'}{\sqrt{\gamma p_3 / q_3}} = r_0 \left( \frac{3 \pi}{4} \right)^{1/3} M_3 \dots\dots\dots (8)$$

Changes of the flow speed through the shock layer can be computed theoretically from usual shock relations for a fluid of inviscid and of negligible thermal conductivity. Mach number of the gas immediately behind the shock is

$$M_2 = \left[ 1 - \frac{M_1^2 - 1}{1 + \frac{2 \gamma}{\gamma + 1} (M_1^2 - 1)} \right]^{1/2} \dots\dots\dots (9)$$

and for the one at the tail where the gas has expanded reversibly back to the upstream pressure, viz.,  $p_1 = p_3$ ,

$$M_2 = \left[ \left( M_1^2 + \frac{2}{\gamma-1} \right) \left( \frac{M_1^2-1}{1-M_2^2} \right)^{\frac{\gamma+1}{\gamma}} - \frac{2}{\gamma-1} \right]^{1/2} \dots\dots\dots (10)$$

The pressure relation across the shock gives

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1} (M_1^2 - 1) \dots\dots\dots (11)$$

Assuming an isentropic condition behind the shock,

$$\frac{p_0}{p_2} = \left( 1 + \frac{\gamma-1}{2} M_2^2 \right)^{\frac{\gamma}{\gamma-1}} \dots\dots\dots (12)$$

From equations (9), (11) and (12), the pressure at the stagnation point  $p_0$  is given as

$$p_0 = p_1 \left\{ 1 + \frac{2\gamma}{\gamma+1} (M_1^2 - 1) \right\} \left[ 1 + \frac{\gamma-1}{2} \left\{ 1 - \frac{M_1^2-1}{1 + \frac{2\gamma}{\gamma+1} (M_1^2-1)} \right\} \right]^{\frac{\gamma}{\gamma-1}} \dots\dots\dots (13)$$

For  $M_1^2 \gg \frac{1}{4}$  and  $\gamma = 2$ , the equation (13) is reduced to

$$p_0 \simeq \frac{81}{64} p_1 \left\{ 1 + \frac{4}{3} (M_1^2 - 1) \right\} \simeq \frac{5}{6} \rho_1 U^2 \dots\dots\dots (14)$$

It is very interesting to note that the pressure exerted at the geomagnetic cavity boundary is nearly equal to  $\rho_1 U^2$ , which is the same as that of free molecular flow of inelastic collisions.

These theoretical results may be compared with the numerical quantities, which are derived from the observed magnetospheric pattern, so that the nature of solar plasma streams can be inferred. To begin with, however, we may tentatively assume the density, magnetic field and temperature of the plasma stream, i.e.,  $n = 5/\text{cm}^3$ ;  $h = 10$  gamma and  $T = 3 \times 10^5$  °K. These values are well within a range a range obtained by various deep space probes mentioned earlier. The characteristic velocities

of both acoustic and hydromagnetic waves are, then, of the order of 100 km / sec, indicating the balance of the thermal and magnetic pressures.

The Mach number of the plasma stream can be estimated independently both from the shape of shock front and from its stand-off distance. The former yields approximate values of 2 - 5, and the value  $M_1 \simeq 3$  is found to be consistent for the latter. The speed of solar plasma streams is, therefore, of 400 - 500 km / sec, which accords with the experimental result obtained by Mariner II (Neugebauer and Snyder 1962). The comparison with the observed and theoretically computed values of the magnetospheric boundaries is shown in Table 2. The agreement between these is remarkable, and this fact will substantiate both the interpretation and the correctness of tentatively assumed values of solar plasma streams.

#### 4. Discussion

The experimental results obtained by recent space probes have revealed evidences of the geomagnetic cavity and the turbulent magnetopause outside of the cavity. The general feature of this geomagnetic cavity structure accords well with the earlier prediction by Axford (1962) and Kellogg (1962). It is now evident that there exists a continual flow of solar plasma with the velocity of 400 - 500 km / sec, streaming past the geomagnetic field. The impact speed is supersonic,  $M = 2 - 5$ , and a standing shock wave is produced a short distance upstream of the geomagnetic cavity.

As has been pointed out by Axford (1962), the shock wave is necessarily of the collision-free type relying on nonlinear interactions of waves to produce the randomization of particle motions. The shock structure and the region downstream appear to be highly turbulent, and this is consistent with the observed nature of the magnetopause.

The plasma flow is slowed down from supersonic to subsonic as it crosses the shock front. The bulk energy of the stream near the forward

stagnation point is almost converted into the form of random thermal motions, and the pressure  $p_0 \simeq \frac{5}{6} \rho U^2$  at the cavity boundary. However, as the stream flows away from this region, the gas expands and the stream is accelerated, eventually becoming supersonic again at greater distances from the shock front.

The size of geomagnetic cavity has been found to be  $r_0 \simeq 10a$  for the day-side and  $r_t \simeq 40a$  for the night-side. It may be noted, however, that this prevails for the geomagnetically quiet period. For an impact of the solar plasma cloud producing a geomagnetic storm, the flow speed is of the order of 1000 km/sec, and hence, the cavity will be compressed considerably. It is known that the magnetic field of such plasma cloud is of 30 - 50 gamma, which has been measured by Pioneer V (Coleman, Sonett and Davis 1961). Assuming that the plasma density of cloud is  $20 \text{ cm}^{-3}$ , the characteristic hydromagnetic velocity is about 200 km/sec, and this yields the Mach number of the flow speed  $M \geq 5$ . For this case, size of the geomagnetic cavity is reduced to  $r_0 \simeq 6.5a$  and  $r_t \simeq 30a$ , and the stand-off distance is only of  $r_s = 8a$ . The geomagnetic latitude where the magnetic field line is connected with near the cavity boundary is approximately  $65^\circ$ , and this seems to be consistent for other geophysical phenomena associated with magnetic storms.

A slight tilt of the shock front, and hence the direction of the plasma flow with respect to the sun-earth line may require further discussion. Some geophysical phenomena in the polar region seem to be related to this problem. The ionospheric current-system derived from geomagnetic variations in the polar-cap is symmetrical across the  $10 \sim 11$  h local time meridian. The characteristic of geomagnetic pulsations at the sudden commencement of storms does indicate that the solar plasma stream impacts from the direction of  $25^\circ$  west of the sun-earth line (Wilson 1962). There is considerable evidence suggesting that solar cosmic ray particles are in fact guided by an extended spiral solar magnetic field, which is

convexed toward the west due to the rotation of the sun (Obayashi 1962, McCracken 1962). These facts may be linked in some extent with the observed asymmetrical nature of the geomagnetic cavity pattern.

In concluding, the writer wishes to thank Dr. Takeo Sakurai for his valuable discussions on hydromagnetic shock waves.

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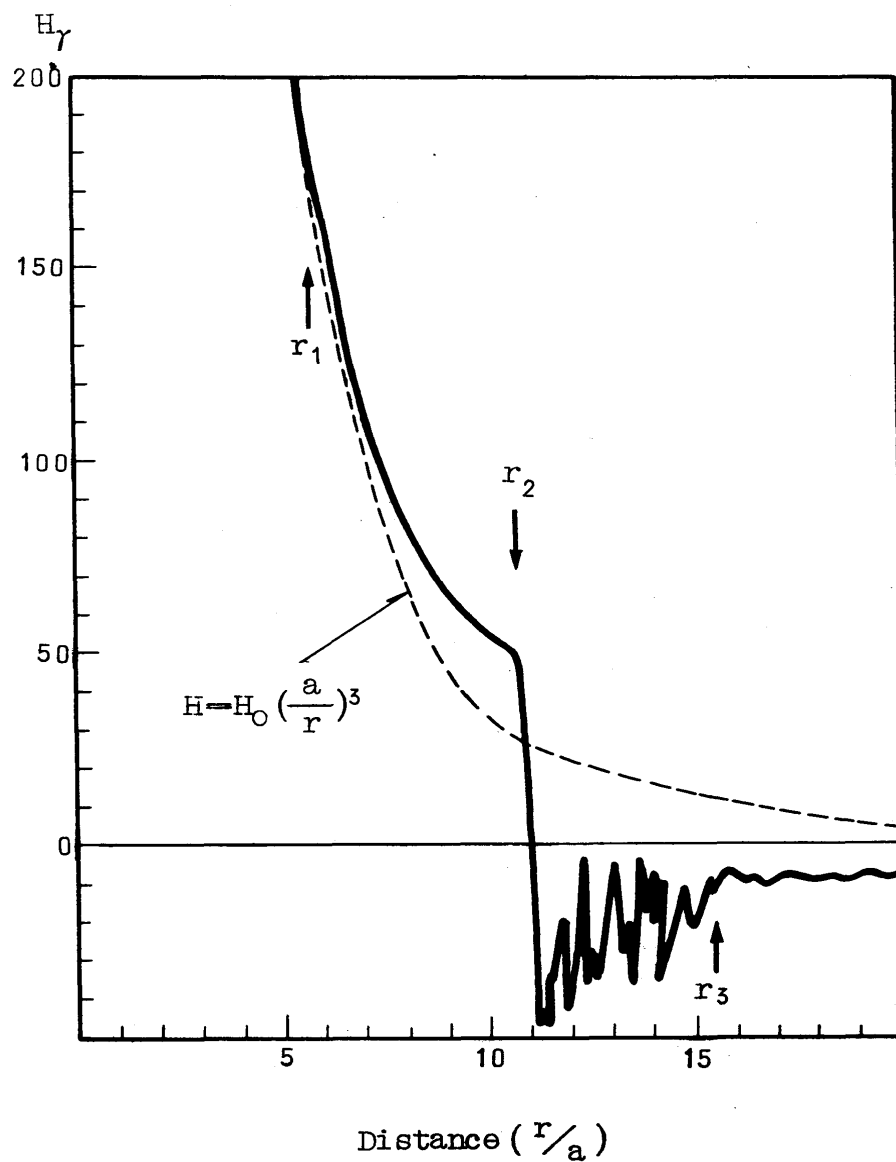


Fig.1 Schematic representation of  
 the outer geomagnetic field  
 (Explorer XII observations,  
 Cahill and Amazeen 1962)

Table.1 Data obtained by space probes 1958-1962

Name	Data	Apogee <sup>(1)</sup>	Azimuth <sup>(2)</sup>	Inclination <sup>(3)</sup>	$r_{1/a}$ <sup>(4)</sup>	$r_{2/a}$ <sup>(5)</sup>	$r_{3/a}$ <sup>(6)</sup>	AP <sup>(7)</sup>
Pioneer I	1958 Oct. 11	18.6a	12.2h	5°		7-12	14	6 Q
Pioneer II	1958 Dec. 6	17.0a	10.0	- 20		(10)	-	12
Lunik I	1959 Jan. 2	*	7.3	- 5	3-5			3 Q
Pioneer IV	1959 Mar. 3	*	8.5	- 18		10	14.5	23
Lunik III	1959 Sept. 12	Moon	21.0	- 7	-	9-12	(30)	14
Lunik IV	1959 Oct. 4	Moon	16.2	- 8				51
Pioneer V	1960 Mar. 11	*	16.5	25	6-8	8-10	25-30	21
Venus IV	1961 Feb. 12	*	(17.5)	(10)				2 Q
Explorer X	1961 Mar. 25	46.6a	20.8	- 35	7	23	-	7 Q
Explorer XI	1961 Aug. 15	13.1a	8-13	- 33	6-7	8-12	-	8 Q
Ranger III	1962 Jan. 26	*						10
Ranger IV	1962 Apr. 23	Moon	no data available in the earths magnetosphere					12
Mariner II	1962 Aug. 27	*						5 Q

(1) \* Interplanetary orbit

(2),(3) Approximate azimuth (longitude in local time) and latitude of the satellite at the distance of 10-20 earths radii

(4) Distance of inner boundary of the magnetosphere ( $a=6370\text{km}$ )

(5),(6) Distance of inner and outer boundary of the magnetopause

(7) Average amplitude of magnetic activity Ap, 24 hours period after launching (Q: international very quiet day)

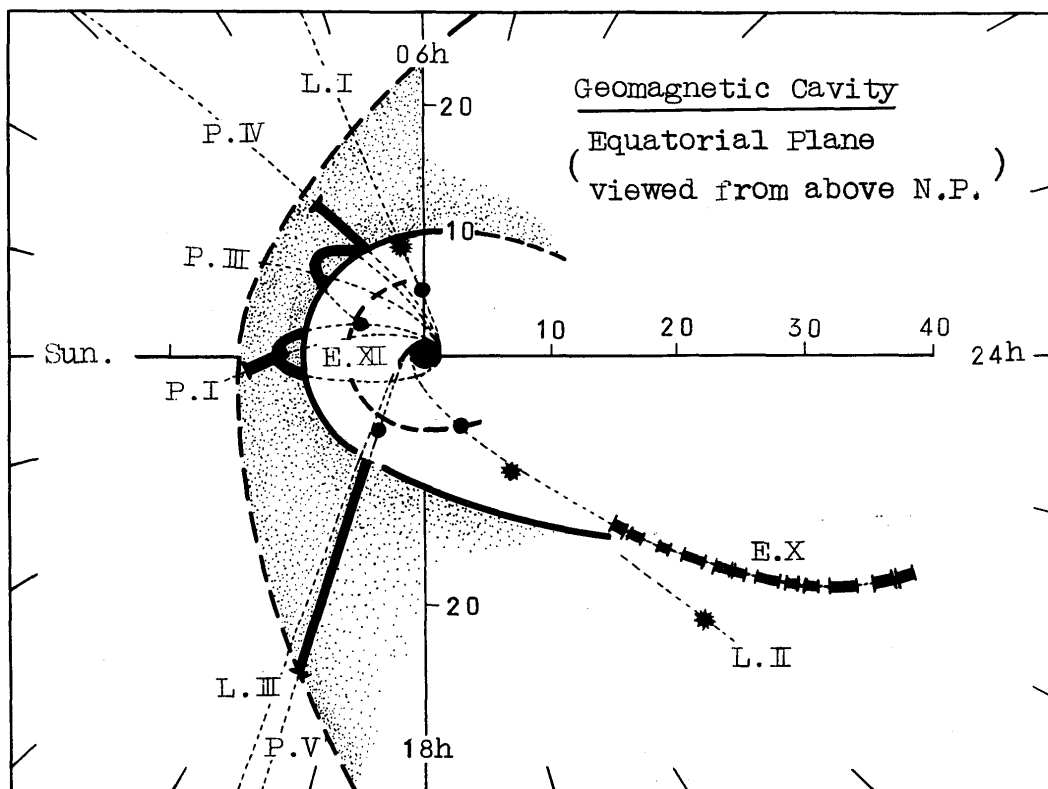


Fig.2 Boundary region of the outer geomagnetic field  
estimated from various space probe observations

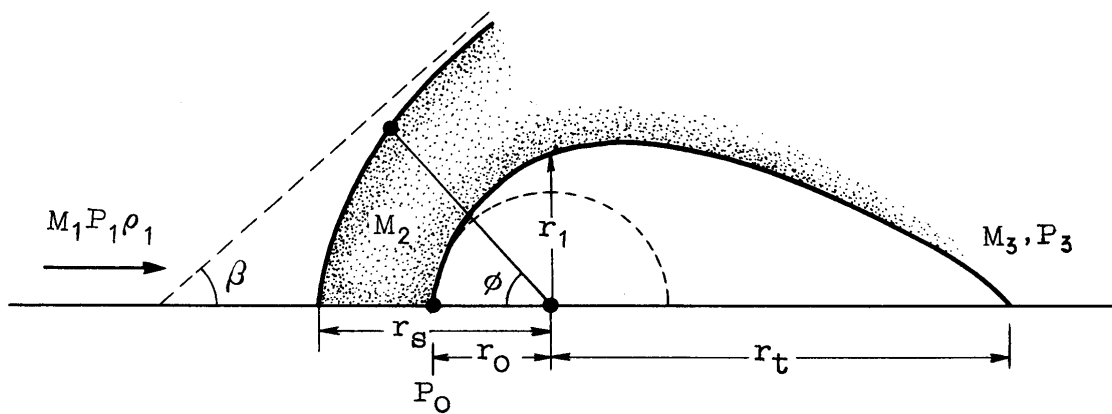


Fig.3 Geometry of a shock front and the geomagnetic cavity

	Estimated	Observed
$V_s$	100 km/s	$2nkT \sim \frac{h^2}{8\pi}$
$V_A$	100	
$M$	3	
(U)	(420 km/s)	
$r_o / a$	11.0	10
$r_s / a$	14.5	14 ~ 15
$r_t / a$	35	> 40

Table.2      Comparison of observed and theoretically  
estimated values of the solar plasma  
stream and of magnetospheric boundaries.