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Abstract

This is a brief summary report on the identifications and analyses of the magnetopause and bow shock crossings at Jupiter based on fine scale magnetic field data from the Voyager 1 and 2 encounters, which occurred (closest approach) on 5 March and 9 July 1979, respectively. Explicit models of the dawnside magnetopause and bow shock in Jupiter's orbital plane employ an axi-symmetric parabola and hyperbola, respectively, and are determined separately for the two encounters. A new phenomenon has been discovered in the magneto-sheath. It is manifested as (5 or) 10 hour quasi-periodic modulation of the direction of the magnetic field in the outbound magnetosheath, predominantly in the northward (N) and southward (S) directions. It was seen to occur during both encounters and appears most evident in Voyager 2 outbound observations, probably due to the extreme tailward extent of the Voyager 2 trajectory through the magnetosheath. The durations of the N $\rightleftarrows$ S transitions range from tens of minutes to $\sim$ 3 hours. The directional variation of the field during these transitions is fairly well restricted to a plane parallel to the local model magnetopause location. These signatures may be due to magnetosheath field line draping modulated by the large scale motion of the magnetospheric plasma disk.

Introduction

The recent Voyager 1 and 2 encounters with Jupiter provide us with the opportunity to study the size, shape, and physical characteristics of the planet's magnetopause (MP) and bow shock (BS) at locations previously unattained, especially during the outbound crossings. This investigation will briefly summarize both inbound and outbound boundary crossings as observed by the magnetometer instruments on both spacecraft and describe a new phenomenon seen to occur in the magnetosheath, also by both spacecraft. Models of the boundaries for average crossing positions will also be presented. This report extends and supplements previous reports on preliminary identifications and analyses of the MP and BS of Jupiter using Voyager magnetic field data (see Ness et al., 1979 a, b).

Observed Magnetopause and Bow Shock Boundaries

Voyager 1 inbound to Jupiter crossed the planet's BS five times on and between February 28 (at 86 R_J) and March 2, 1979 (at 56 R_J); R_J = 71,372 km is Jupiter's radius. The spacecraft's Jovicentric longitude, ϕ_{SC}, during this period was 342° (± 2°), where $\phi_{SC} = 0°$ is toward the sun and longitude is measured positive counterclockwise in Jupiter's orbital plane. There were multiple inbound MP crossings, possibly nine, between March 1 and 3 (i.e., from 67 to 47 R_J). Outbound there were 3 MP crossings and 7 BS crossings occurring from March 16 to 22 (i.e., from 200 to 257 R_J at ϕ_{SC} of $\lesssim$ 245°). About four months later Voyager 2 inbound crossed Jupiter's BS and MP a total of 7 (at least) and 3 times, respectively, over the period July 2 to 5 [i.e., from 99 to 62 R_J at ϕ_{SC} = 334° (± 4°)]. Voyager 2 outbound at $\phi_{SC} \lesssim 226°$ encountered 15 MP crossings and 9 BS crossings from July 23 (at 170 R_J) to August 13 (at $\gtrsim$ 380 R_J).

Table 1 gives a detailed listing of all Voyager 1 and 2 MP and BS crossing times as identified in the magnetic field data. However, the identifications of most of the 17 MP crossings along the Voyager 2 outbound trajectory required coordination with the Voyager Plasma Science Team (J. Belcher and H. Bridge, private communication, 1980). Specifically, identification of these 17 crossings was based on rapid directional changes of the field correlated with plasma electron (10–140 ev) flux changes and plasma ion density changes. All other MP and BS boundaries were identified through the use of magnetic field data as described by Ness et al. (1979a,b). Listings of Voyager 1 and 2 MP and BS crossings as identified in the Plasma Science data only have been presented by Bridge et al. (1979a,b). Except for occasional time shifts, some Voyager 2 BS crossings, and a series of Voyager 1 inbound "MP crossings" late on day 61 (to be discussed below), the magnetometer team's boundary identifications usually agree with those of the Plasma Science team; also our Voyager 2 list is extended to later times than that published by Bridge et al. (1979b). Disagreement in BS identifications are usually due to the the magnetometer team's difficulty in identifying brief occurrences of pulsation shocks. The six Voyager 1 "MP crossings" on day 61 are listed as possibilities, and must remain in some doubt, since they could alternatively be signatures of magnetosheath fields that vary in direction due to variable MP field line draping. This topic will be expanded below with reference to the outbound magnetosheath. These six "crossings" nevertheless possess characteristics similar to the others, in which there is agreement in identification. More will be said below on the peculiar nature of the outbound Voyager 2 MP crossings where plasma science and magnetometer event-signatures are occasionally displaced in time, in one case by as much as 16 min.

Distant ($\sim$ 700 R_J) MP and BS identifications based on outbound Voyager 2 observations have been made (W. S. Kurth and F. L. Scarf, private communication, 1980), but will not be included either in this list or this analysis.

Model Boundaries and Analysis

In Figure 1 of Ness et al. (1979b) Jupiter encounter trajectories of Voyagers 1 and 2 are shown, as well as model MP and BS boundaries, in Jupiter orbital coordinates. In these coordinates the $\hat{X}_o$-$\hat{Y}_o$ axes lie in the planet's orbital plane, $\hat{X}_o$ being positive sunward, $\hat{Z}_o$ is normal to the orbital plane, positive northward, and $\hat{Y}_o = \hat{Z}_o \times \hat{X}_o$. Using average MP crossing positions separately for the two spacecraft, and the assumptions that the dawnside MP and BS are adequately described in the planet's orbital plane as an axially ($\hat{X}_o$) symmetric parabola and hyperbola, respectively, the following model boundaries result:

$$\text{Voyager 1 MP: } Y_o = -[168 R_J (57 R_J - X_o)]^{1/2}, \qquad (1)$$

$$\text{Voyager 2 MP: } Y_o = -[102 R_J (68 R_J - X_o)]^{1/2}, \qquad (2)$$

$$\text{Voyager 1 BS: } Y_o = -0.712 [(242 R_J - X_o)^2 - 28{,}900 R_J^2]^{1/2}, \qquad (3)$$

and

$$\text{Voyager 2 BS: } Y_o = -0.380 [(569 R_J - X_o)^2 - 236{,}000 R_J^2]^{1/2}. \qquad (4)$$

Since neither Voyager spacecraft traversed the duskside boundaries, which was also true for Pioneers 10 and 11, we can say little about the duskside portion of the models; hence, Y_o is made explicitly negative in equations (1) through (4). Aberration due to planetary motion with respect to the solar wind speed is negligible, but a severe asymmetry may still exist, at least at lower latitudes near Jupiter because of the rapid rotation of the planet and plasma loading at lower latitudes. Although the MP stagnation point is obviously very variable, its average distance from Jupiter's center was similar for the two Voyagers ($\sim 65\ R_J$) and was on average for the two Pioneers $\sim 75\ R_J$ (Smith et al., 1974, 1975, 1976).

Table 2 summarizes the number of crossings, their associated planetocentric radial ranges, the longitude (λ (Model)) of the normal to the model MP, and latitude (δ) and longitude (λ) of the average of the "well-estimated" MP normals; λ and δ are in heliographic coordinates. By definition the heliographic coordinate system angles λ, δ are:

$$\lambda = \tan^{-1} (X_T/X_R),$$

and

$$\delta = \sin^{-1} (X_N/X),$$

where

$$X = (X_R^2 + X_T^2 + X_N^2)^{1/2},$$

and where the spacecraft centered orthogonal unit vectors are defined such that $\hat{R}$ is along the sun-spacecraft line, positive away from the sun; $\hat{T}$ is normal to $\hat{R}$ and is parallel to the sun's equatorial plane, positive in the direction of planetary motion; and $\hat{N} = \hat{R} \times \hat{T}$. The X_i's then represent either components of the field or normal components. The individually estimated MP normals were obtained through the use of the Sonnerup-Cahill (1967) minimum variance technique as applied to 1.92 s averages of the magnetic field; see Lepping and Behannon (1980) for a discussion of what is meant by "well-estimated" cases and for a criterion for choosing discontinuity (MP) by type. Excluding one unusually long MP transition (35 min. for the first Voyager 1 outbound MP), the minimum variance analysis intervals were 6.1 min. on average with a standard deviation of 3.2 min. over all the remaining well-estimated transitions. Considering only the well-estimated cases, almost all ($\gtrsim$ 87%) of the MP discontinuities were of the tangential type. Table 2 shows that, except for the outbound Voyager 2 MP crossings, the agreement between the average estimated and model normals is quite good; it is assumed that δ(Model) $\equiv 0^{\circ}$. The average normals were based on the well-estimated cases, which included most of them for the top three categories; the table also gives the number of these cases for each category. Only two of the seventeen outbound Voyager 2 MP crossings provided results consistent with the model normal; however, three occurred in data gaps and did not permit analysis (see Table 1). There was considerable scatter in the fourteen remaining normal directions and some were displaced by $\gtrsim 90^{\circ}$ from the expected (modeled) direction, given by Equation 2, as if a turbulent boundary was encountered.

10-Hour Modulation in the Magnetosheath Field Structure

A new phenomenon has been discovered in the magnetosheath (MS) of Jupiter. Large scale (many minutes to ~10 hours) magnetic field structures, consisting predominantly of approximately North-South (N-S) field directions, have been observed by Voyagers 1 and 2 during their outbound encounter trajectories. This phenomenon is illustrated in Figure 1 which shows approximately two days of Voyager 2 field data (48 s averages) when the spacecraft was predominantly in the outbound MS, i.e., except for the last five hours when it was again engulfed by the magnetosphere, where the field is generally more steady and at typically lower latitudes. The λ variation is partially misleading during some intervals, because of the very high (+ and -) inclinations of the field then. The centers of the N-S transitions are often ~5 (or ~10) hours apart, and sometimes pairs of structures total ~10 hours duration, even when their two segments are significantly different from 5 hours.

Figure 2 shows the field latitude angle δ measured by Voyager 2 during a period of approximately nine days outbound in the Jovian magnetosheath. It is plotted as a function of λ_{III}, i.e., System III longitude (1965). During most of the central four day gap the spacecraft was in the magnetosphere. It is immediately evident that approximately five and ten hour structures dominate the overall pattern of changes in δ, although there is no strictly repetitive periodicity in its variation. However, it is found that the centers of many major changes occur faithfully near λ_{III}'s of $\backsim 5^{\circ}$ and $\backsim 200^{\circ}$ within $\backsim 40^{\circ}$ (i.e., within $\backsim$ 1 hour). Also evident is the relatively large number of boundary crossings, both MP and BS, occurring near λ_{III} values of $\backsim 15^{\circ}$ especially and at 225° occasionally, with a similar angle spread. This near alignment in time of the δ-features with some of the MP and BS crossings is remarkable.

A minimum variance analysis of the field using 48 s averages for seven intervals (labeled as horizontal bars), which were on average 2-1/2 hours in length, was carried out in order to compute the normals to the minimum variance planes of the large MS features. The seven normals were then averaged. The results of the analysis are presented in Table 3 along with the expected MP modeled-normal (from Equation 2) in the vicinity of the spacecraft for these times, for comparison. Also given are the computational results for similar features seen in the Voyager 2 inbound MS and for both the inbound and outbound Voyager 1 MS. The good agreement between the average normals and the model normals suggests that the former were delineating the true MP boundary normals, as well as, or (for Voyager 2) better than, the (expected) thin transitions zones of the MP current sheets themselves. Some apparent large scale "δ-features" which occurred in the interplanetary medium just outside the Voyager 2 outbound BS did not yield normals parallel to the local MP boundary when studied by means of a minimum variance analysis.

Summary and Discussion

By assuming symmetry about the X_o-axis ($\hat{X}_o$ points toward the sun), the

Voyager 1 and 2 "average" dawnside MP shapes in the orbital (X_o-Y_o) plane of Jupiter are reasonably well represented, over the region of the trajectories, by parabolas (see Equations (1) and (2)). Properties of these boundaries, such as their normals and type, have been estimated using minimum variance analyses of the magnetic field. The average inbound and outbound normals and crossing positions generally satisfy this model, to within a few degrees for the average normals, in all except the Voyager 2 outbound cases where large normal scatter was obtained and where significant time displacement occasionally appeared between plasma science and magnetometer identifications. There is a suggestion of the presence of a turbulent boundary at that time.

The Voyager 1 and 2 average dawnside bow shocks are well represented by hyperbolas (see Equations (3) and (4), over the same region). Magnetic fields with very high latitudes (+ and -) were observed in the Voyager 1 and 2 outbound MS with either broad or sharp transitions (North ↔ South) occurring ~5 or ~10 hours apart for many days. The intensity of the field also experienced this modulation, and some outbound (Voyager 2 especially) MP and BS crossing times were apparently related to this temporal effect. As the spacecraft traversed the outbound MS, the probability of occurrence of these large structures appears to decrease. Analysis indicates that the minimum variance direction of the field of these structures for Voyagers 1 and 2 is normal to the local MP as given by the model fits (Equations (1) and (2)) to the crossing positions. This was not the case for similar large-scale structures seen in the interplanetary medium (also showing unusual N-S directions, but usually of less severity), although only a few interplanetary cases were analyzed.

The occasional synchronization of the north $\pm$ south MS features with either MP or BS crossings, as seen in the outbound Voyager 2 data (see Figure 2), is apparently not coincidental. Dessler and Vasyliunas (1979) suggest a range in subspacecraft λ_{III} coordinates in which the Voyager MP crossings might be expected to occur according to predictions of the magnetic anomaly model. The longitude of greatest occurrence of $\lambda_{III} \approx 15^o$ was the longitude of greatest occurrence of Voyager 2 outbound MP crossing positions and this lies just outside their predicted range $225^o \leq \lambda_{III} \leq 355^o$. We believe a more likely explanation for the synchronization of some of the MP and BS crossings with the large scale δ-changes in the MS lies in understanding the motion and configuration of the magnetosphere current sheet (responsible for the crossings) and its synchronization with the motion of the entire magnetosphere boundary, which in turn probably influences the MS plasma flow and its embedded field. With regard to the form of the MS field structures, it is not unreasonable that they were found to consist of (N-S) variations in planes parallel to the local large scale MP, if they were caused by interplanetary field line draping as these field lines convected through the BS and encountered the MP. The MS plasma and its embedded field should be modulated every 5 or 10 hours (depending on the exact nature of the interaction) due to the rocking of a flattened frontside MP, i.e., flattened approximately along the direction of the planet's magnetic dipole moment. We are presently pursuing these ideas, which will be incorporated in a more comprehensive paper on the MS observations (Lepping et al., 1981).

Preliminary correlations of field variations with plasma velocity variations (J. Belcher and J. Jessen, private communication, 1980) in the outbond MS's of Voyagers 1 and 2 indicate the very likely probability that the large scale MS fluctuations described here are Alfvénic in character with a propagation speed, relative to the flowing plasma, of $\sim$ 70 km/s. This analysis will be pursued more fully (Lepping et al., 1981).

The inability to obtain "reasonable" outbound MP normals using minimum variance analyses which agree with a simple model, such as those given by Equations (1) and (2), may be due to the complicated nature of the downstream MP and its motion. [It is possible that the outbound MP at Voyager 2's position is complex in structure due to influences internal to the boundary; this is the region where Krimigis et al. (1979) observe a magnetospheric wind.] Since the large scale MS structures yield normals in close agreement with the models of Equations (1) and (2), one is led to believe that these models give a representation of the very large scale configuration of the average outbound boundary, but not necessarily the actual instantaneous local normal.

Gurnett et al. (1979) report on a broad boundary layer region existing between Jupiter's MP and the inner corotating portion of the magnetosphere; on Voyager 2's outbound leg this broadens into a region bounded by the MP and an inner tail-like region throughout which the "magnetospheric wind" of Krimigis et al. (1979) blows. Gurnett et al. (1979; also see references therein) point out that within this boundary layer 10-hour features apparently are completely absent. If this is correct, we are faced with the apparent dilemma that the 5/10 hour MS features are radially separated from inner magnetospheric 5/10 hour features by a broad region wherein no modulation occurs. If our qualitative model described above is correct, however, there is no dilemma, because the MS features are not assumed to propagate radially from Jupiter, but originate upstream in the MS, due to MP rocking motion. All that we require is that somewhere an internal rocking motion is transferred to the MP boundary, and hence to the MS.

Finally, the inbound Voyager 1 and 2 MP crossings occurred over radial distances ranging from 47 to 72 R_J. By comparison, Pioneers 10 and 11 inbound MP crossings average to ~ 75 R_J with even greater variability (Smith et al., 1974, 1975, 1976). All four spacecraft approached Jupiter at $\phi_{SC} \approx 330^o \pm 13^o$, so radial comparisons of the inbound crossings are reasonable. This also means that at low latitudes only a small range of ϕ_{SC} has yet been covered for studies of the frontside BS or MP.

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TABLE 1

VOYAGER MAGNETOPAUSE AND BOW SHOCK BOUNDARIES

VOYAGER 1			VOYAGER 2					
TYPE	DAY†	HOURS, MINUTES†	TYPE	DAY†	HOURS, MINUTES†	TYPE	DAY†	HOURS, MINUTES†
BS	59	1434	BS	183	1621	MP	212/213	1733-0605**
BS	59	1954	BS	183	1623	MP	213	1517
BS	60	1227	BS	183	1645	MP	213	1539-1602**
MP	60	1956	BS	183	1925	MP	214	0222
MP	61	0754	BS	184	1736	MP	214	0722
BS	61	0950	MP	185	2337	MP	215	0611
BS	61	1308	MP	186	0110	MP	215	0723 ?
MP*	61	1430	BS	186	0522	MP	215	0728 ?
MP*	61	2003	BS	186	0955	MP	215	0757
MP*	61	2045	MP	186	1840	BS	215	1441
MP*	61	2112	MP	204	1522-2340**	BS	215	1625
MP*	61	2153	MP	205	0135	BS	215	1703
MP*	61	2228	MP	205	0531	BS	216	0300
MP	62	0227	MP	205	0557	BS	217	0940
MP	74	0930	MP	205	0917	BS	217	1825
MP	74	1700	MP	206	0052	BS	225	0508-1254**
MP	74	2119	MP	206	0410	BS	225	1418
BS	77	0706	MP	208	1820	BS	225	1809
BS	79	0808						
BS	79	0827						
BS	80	0738						
BS	80	2107						
BS	81	0941						
BS	81	1303						

† DAY refers to day of year 1979 where 1 January = 1, and time is given in spacecraft UT.

* Identifications of these MP crossings are in doubt. See text.

** Gap in data.

TABLE 2

SUMMARY OF VOYAGER BOUNDARY CROSSINGS AND NORMALS

SPACECRAFT	BOW SHOCK NO.	BOW SHOCK DISTANCE (R_J)	MAGNETOPAUSE NO.	(NO)*	DISTANCE (R_J)	NORMAL AVERAGE EST. δ	NORMAL AVERAGE EST. λ	NORMAL MODEL λ
VOYAGER-1								
INBOUND	5	86↔56	9	(8)	67↔47	3°	165°	168°
OUTBOUND	7	199↔256	3	(3)	158↔165	7°	124°	120°
VOYAGER-2								
INBOUND	7	99↔66	3	(2)	72↔62	-1°	155°	152°
OUTBOUND	9	282↔$\gtrsim$380	17	(2)	170↔279	?	?	109°

(NO)* refers to the number of well-estimated cases; see text.

TABLE 3

AVERAGE NORMALS FOR LARGE SCALE MAGNETOSHEATH STRUCTURES

	SPACECRAFT	NO.	λ_{HG} MIN-VAR	λ_{HG} MODEL	δ_{HG} MIN-VAR	δ_{HG} MODEL
INBOUND	VOYAGER-1	1	157°	168°	7°	0°
	VOYAGER-2	3	159°	152°	0°	0°
OUTBOUND	VOYAGER-1	7	110°	120°	6°	0°
	VOYAGER-2	7	107°	109°	0°	0°

Figure Captions

Figure 1. Approximately two days of Voyager 2 outbound magnetosheath magnetic field data (48 s averages) in the form of: B, the magnitude; λ, the longitude, and δ, the latitude, in heliographic coordinates (see text for definition of coordinates). The last 5-1/2 hours are magnetosphere data as denoted. Time is given in spacecraft UT.

Figure 2. Voyager 2 magnetic field latitudes (δ) as a function of System III longitude (1965.0) of spacecraft primarily in the outbound magnentosheath; regions of magnetosphere and interplanetary magnetic field (IMF) are designated. Individual points represent 48 s averages and tic marks occur every 3 hours (or once a day for larger tic marks). Day of year, and fraction of day, are given for the start of each panel for approximately 9 days. Dark horizontal bars represent intervals for which minimum variance analyses were performed.

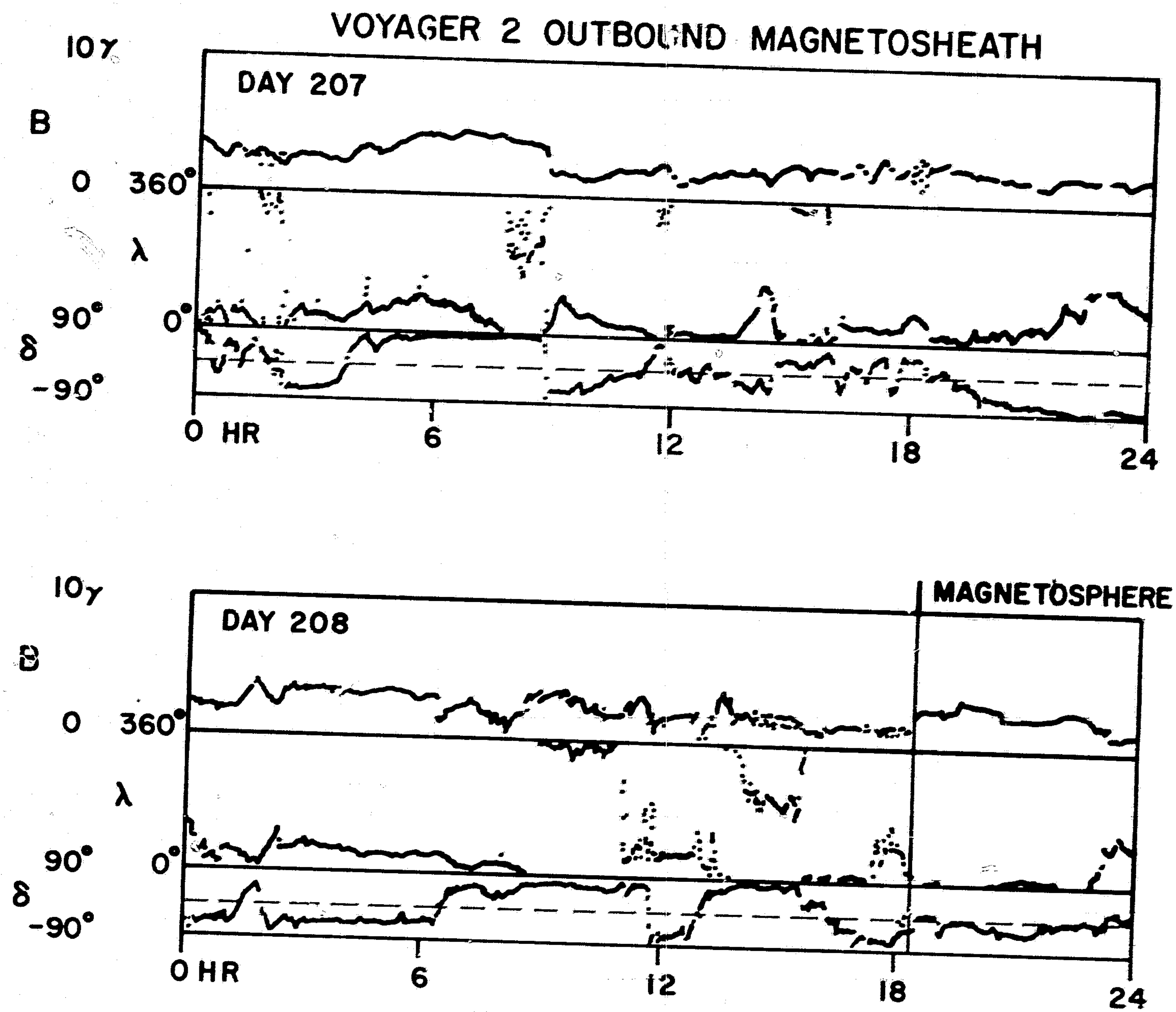
VOYAGER 2 OUTBOUND MAGNETOSHEATH
DAY 207
10γ
B
0
360°
λ
0°
90°
δ
-90°
0 HR
6
12
18
24
DAY 208
MAGNETOSPHERE
10γ
B
0
360°
λ
0°
90°
δ
-90°
0 HR
6
12
18
24

Figure 1

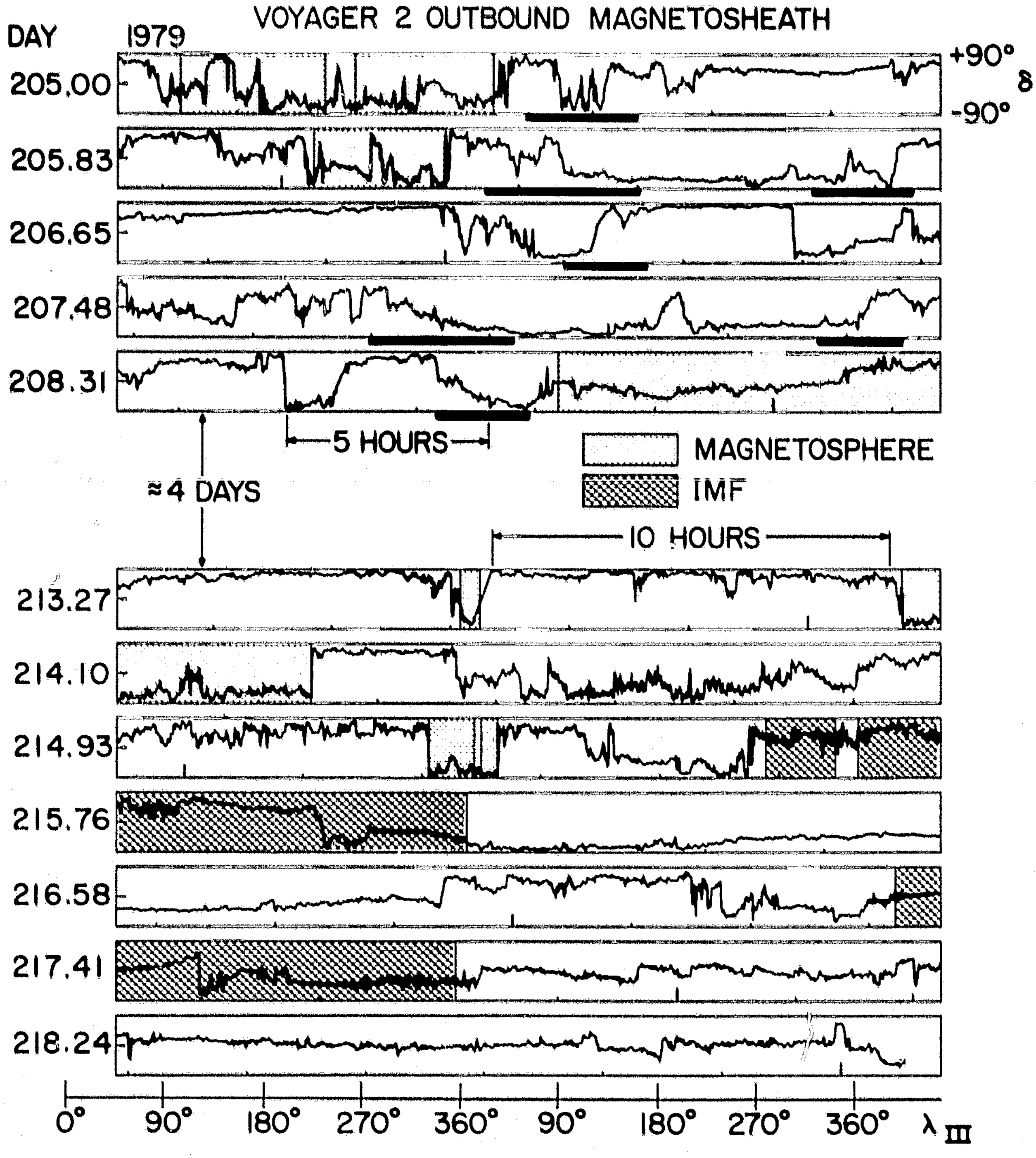
VOYAGER 2 OUTBOUND MAGNETOSHEATH
DAY
1979
205.00
205.83
206.65
207.48
208.31
+90°
δ
-90°
5 HOURS
≈4 DAYS
MAGNETOSPHERE
IMF
10 HOURS
213.27
214.10
214.93
215.76
216.58
217.41
218.24
0°
90°
180°
270°
360°
90°
180°
270°
360°
λ III

Figure 2