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AND BOUNDARY REGIONS

by

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ABSTRACT

In 1979-1981, the three USA spacecraft Pioneer 11 and Voyagers 1 and 2 discovered and explored the magnetosphere of Saturn to the limited extent possible on flyby trajectories. Considerable variation in the locations of the bow shock (BS) and magnetopause (MP) surfaces were observed in association with variable solar wind conditions and, during the Voyager 2 encounter, possible immersion in Jupiter's distant magnetic tail. The limited number of BS and MP crossings were concentrated near the subsolar region and the dawn terminator, and that fact, together with the temporal variability, makes it difficult to assess the three-dimensional shape of the sunward magnetospheric boundary. The combined BS and MP crossing positions from the three spacecraft yield an average BS-to-MP stagnation point distance ratio of 1.29 ± 0.10. This is near the 1.33 value for the earth's magnetosphere, implying a similar sunward shape at Saturn. Study of the structure and dynamical behavior of the outer magnetosphere, both in the sunward hemisphere and the magnetotail region using combined plasma and magnetic field data, suggest that Saturn's magnetosphere is more similar to that of Earth than that of Jupiter. Also, evidence was found by Voyager 1 for tailward flowing plasma near the pre-dawn MP, a phenomenon well known for the cases of both Earth and Jupiter. That this was not observed by Voyager 2 at Saturn may have been related to the possible immersion of Saturn in Jupiter's magnetotail during a significant portion of the Voyager 2 encounter period, since the plasma flux in the Jovian tail is markedly lower than that in the solar wind on average.

INTRODUCTION

Various characteristics of the magnetic fields and plasma in the outer magnetosphere and boundary regions of Saturn's magnetosphere have been investigated both by instruments onboard the Pioneer 11 (P11) spacecraft (Smith et al., 1980 a,b; Wolfe et al., 1980) and by Voyagers 1 and 2 (V1 and V2) (Ness et al., 1981, 1982; Bridge et al., 1981, 1982; Gurnett et al., 1981; Krimigis et al., 1981, 1982; Scarf et al., 1982; Lepping et al., 1981a; and Behannon et al., 1981). These measurements were made during 1979, 1980 and 1981 (closest approaches on 1 September, 12 November and 26 August, respectively) and demonstrated a notable temporal variability in the size and possibly the shape of the Saturnian magnetosphere.

Prior to the Voyager encounters, there was speculation concerning a possible significant expansion of the magnetosphere if Saturn became immersed in the extended magnetic tail of Jupiter (Scarf, 1979; Wolfe et al., 1980). It was suggested that this might occur at the time of the V2 - Saturn encounter because of the nearly radial alignment of Jupiter and Saturn at that time. There is indirect evidence from V2 that this may have taken place, with intervals of anomalous, "tail-like" fields and plasma observed in the solar wind by V2 during a period of at least 8 months prior to the Saturn encounter (Scarf et al., 1981; Kurth et al., 1981, 1982b; Lepping et al., 1982, 1983). In addition, a significantly expanded Saturnian magnetosphere was seen by V2 outbound from Saturn (Ness et al., 1982; Bridge et al., 1982; Scarf et al., 1982), and nonthermal continuum radiation due either to intrinsic sources or to the Jovian tail was detected within the magnetosphere (Kurth et al., 1982a). The latter fulfills a necessary but not sufficient condition for possible leakage of such radiation from the Jovian magnetotail into Saturn's environment. Changes seen in the magnetic field during traversal of the dayside outer magnetosphere by V2 suggest that the expansion may have occurred at that time (during 1000-1600 UT on day 237) and persisted until after the spacecraft had crossed the magnetopause and bow shock outbound (Ness et al., 1982), i.e., lasting ~4.5 days.

The purpose of the present paper is to present as nearly as possible with the limited data available a global picture of Saturn's outer magnetosphere and boundary regions, based upon comparative analysis and interpretation from V1 and V2 combined magnetic field and plasma measurements. This will include consideration of the differences between the observations by various spacecraft, with emphasis on the possible causal role played by the extended magnetic tail of Jupiter. One question which is addressed and discussed is that of the three-dimensional shape of the sunward magnetospheric boundary of Saturn. Evidence will be presented also for the existence and variability of tailward-directed plasma flows in the Saturnian magnetosphere near the dawn-side magnetopause. A companion paper (Connerney et al., 1983) describes important features of the inner Saturnian magnetosphere, including the distorting influence of the azimuthal equatorial ring current system.

OBSERVATIONS

Shape of the Dayside Magnetosphere

At Saturn, as at Earth and all other magnetospheric obstacles in the solar wind, the locations of bow shock (BS) and magnetopause (MP) boundaries relative to the planet depend on the state of the solar wind and thus are variable in time. These variations, as well as average boundary locations, have been studied in detail for the case of the earth's magnetosphere (e.g., Fairfield, 1971; and also see Formisano, 1979, on variations in the orientation and shape of the bow shock).

In the case of Saturn, the encounter observations suggest that during two of the three encounters to date (P11 and V2) there were large changes in either the boundary locations or their shapes between the inbound and outbound legs of the trajectories, i.e., on a time scale less than or equal to the time required for transit of the magnetosphere, ~4 days (Wolfe et al., 1980; Ness et al., 1982; Bridge et al., 1982). This has made it difficult to obtain an accurate estimate of the sub-solar BS-to-MP distance. The distance ranges over which BS and MP boundary crossings were observed, as well as the number of crossings, are summarized for both Voyagers and for P11 in Table 1. The implication, particularly from V1 data (discussed in detail below), is that at Saturn the sub-solar magnetosheath thickness in proportion to the MP distance is less than at Earth, where the subsolar BS-to-MP distance ratio, R_{BS}/R_{SP}, with SP denoting stagnation point, is characteristically 1.33 or at Jupiter, where this ratio has been inferred from V1 and V2 observations to lie between 1.22 and 1.26 (Lepping et al., 1981b).

It has been suggested that the ratio R_{BS}/R_{SP}, or more specifically the related ratio $\Delta R/R_{SP}$, where $\Delta R = R_{BS} - R_{SP}$ is the stagnation point detachment or standoff distance, provides a semi-quantitative measure of the degree of bluntness of the front-side magnetosphere (Lepping et al., 1981b). The assumed relationship between $\Delta R/R_{SP}$ and "degree of bluntness" of an obstacle in a flow is based on results from the study of the hypersonic aerodynamics of bodies of revolution (Hayes and Probstein, 1966; Krasnov, 1970). It is known from the hypersonic flow studies that the bow shock is attached to the nose of a sharply-pointed (or wedge-shaped) obstacle. The effect of blunting the nose of a pointed object is to displace the shock away from the body (Cox and Crabtree, 1965), with the detachment distance increasing with increasing bluntness, at least in progressing from a spherical body, for example, to a flat-nosed body, all other important parameters being kept equal (see for example Figure 1 in Freeman, Cash and Bedder, 1964).

In the case of Jupiter, Lepping et al. (1981b) concluded on the basis of the aerodynamic analog that a lower value of $\Delta R/R_{SP}$ is to be expected if the Jovian magnetosphere presents a less blunt obstacle to the solar wind than does Earth's magnetosphere, which has a nearly spherical sunward profile. This would be true if, for example, the Jovian magnetosphere were flattened significantly along approximately the direction of the planetary rotation axis. Although there are indications from P10 and the Voyager spacecraft that this is indeed the case (Engle and Beard, 1980; Lepping et al., 1981b), there is also conflicting evidence from P11, which entered the magnetosphere at a local time of 0900 and latitude of $-7°$ and exited near local noon at higher latitude ($\sim 32°$), that the sunward Jovian magnetosphere as a whole tends to be more spherical than disk-shaped (Smith et al., 1975); this dilemma may be explained if a significant solar wind ram pressure decrease took place between the P11 inbound and outbound legs.

An estimate of the subsolar BS to MP distance ratio for Saturn based only on an average of V1 inbound crossing positions is 1.11. Fits of hyperbolic and parabolic curves to the mean observed inbound and outbound crossing positions of the BS and MP, respectively, by V1 give an almost identical estimate of 1.12. The resulting boundaries in cylindrical coordinates are illustrated on the left-hand side in Figure 1, along with the spacecraft trajectory.

That this value for Saturn with its Earth-like magnetospheric shape is even lower than that for Jupiter is rather puzzling, since it suggests an ordering of the values by heliocentric distance, whereas, if the gas dynamic analog is correct, the standoff ratio should be insensitive to the changes that occur in the characteristics of the solar wind with distance from the sun. If, on the other hand, this ratio for Saturn is estimated using combined V1, V2 and P11 encounter data, where again it should be noted that there was considerable solar wind variability during the V2 and P11 encounters and therefore greater uncertainty in their use, the much larger average value 1.29 ± 0.10 is obtained. This lies between the values for Earth and Jupiter and is thus consistent with the Saturn's magnetosphere having a sunward profile that is less blunt than Earth's but more blunt than Jupiter's. The model boundaries shown in Figure 1 lead to the same conclusion.

Slavin et al. (1983) have computed a shape for Saturn's sunward magnetopause also, assuming cylindrical symmetry and fitting P11 and Voyager boundary crossing locations (excluding V1 outbound) that have been normalized by estimates of external plasma pressure. The resulting model suggests that the Saturnian magnetosphere is blunter at the nose than that of the earth, seemingly in direct contradiction with the above conclusion. This issue will be discussed in the Summary and Discussion section.

Magnetopause Response to External Pressure Variations

As indicated in the preceding discussion, solar wind conditions were relatively quiet during the period of the V1 encounter as evidenced by single inbound and outbound shock crossings, at 26.1 R_S near the noon meridian and at 77.4 R_S tailward of the dawn meridian, respectively. The multiple MP traversals inbound were interpreted to be waves on the magnetosphere boundary (Lepping et al., 1981a) and probably not associated with instantaneous changes in solar wind ram pressure. In fact, the estimated subsolar magnetosheath thickness based on the BS and MP quadratic models was consistent within ~20 % with the observed duration of the magnetosheath crossing multiplied by the spacecraft speed (2.4 R_S), supporting the supposition of a steady solar wind at that time and a stationary configuration of the BS and MP surfaces, on average.

In the case of the P11 encounter, the arrival of a fast solar wind stream just prior to encounter compressed the magnetosphere, so that the inbound shock crossing distances ranged from 20 to 24 R_S (Smith et al., 1980b). The bow shock was observed by P11 outbound to be considerably farther from Saturn than expected; this was attributed to a relaxation of solar wind conditions back to the quiet state during the spacecraft's traversal of the magnetosphere (Smith et al., 1980b).

A similar enhancement of the solar wind and interplanetary magnetic field (IMF) occurred prior to the V2 encounter. An interplanetary shock wave passed the spacecraft at ~1400 UT on August 21, 1981 (day 233). Field magnitude increased from < 0.7 nT to > 1.0 nT with essentially no change in direction. Simultaneous increases in both the density and the speed of the solar wind were seen (E. C. Sittler, private communication). Approximately 12 hours later, a change of ~180° in the azimuth of the IMF was observed, indicating a transition of the interplanetary current sheet. Field magnitude and solar wind density and speed values were still elevated at the time Saturn's BS was reached at 1337 UT on day 236, and Saturn's MP was found to be compressed (to ~19 R_S) relative to the locations observed by V1 (see Figure 1), but not as compressed as observed by P11 inbound (~17.3 R_S).

V2 crossed the near-noon bow shock a total of 5 times over a distance ranging from 23.6 to 31.5 R_S. Outbound MP and BS locations at local times of 0530 and 0540, respectively, were markedly displaced outward relative to positions expected from the inbound observations, indicating that a drastic change in conditions external to the magnetosphere occurred during the 82 hours that the spacecraft was inside the magnetosphere. This change is illustrated on the right-hand side of Figure 1. A study of solar wind conditions over the preceding nine months using Voyager Plasma Science (PLS) data suggested that the Saturnian magnetosphere may have been as expanded as found by V2 outbound only $\sim$3 percent of the time during that period (Bridge et al., 1981) based on the theoretical ram pressure relation. This suggests that it would have been highly coincidental for there to have been such a marked drop in solar wind ram pressure during the V2 encounter. It further has been determined that there apparently have been no occasions during which the magnetosphere has been as greatly expanded for as <u>long</u> as it appeared to be in this case ($\sim$4 days), again based on actual extensive Voyager PLS solar wind data and the ram pressure argument (Kurth et al., 1982a). However P11 also observed a significant change in size.

As mentioned in the introductory remarks, an alternative explanation is that Saturn passed through the distant Jovian magnetotail (or tail filaments) at this time, which would be expected to produce a similar effect of greatly reduced pressure. Prior to the Saturn encounter, recurring anomalous magnetic field, plasma, plasma wave and radio wave features were interpreted as detections by V2 of the Jovian tail at distances as far as $\gtrsim$9000 R_J from Jupiter, the last sighting occurring about one week before Saturn encounter (Kurth et al., 1982b; Lepping et al., 1983). Additional, post-Saturn Jovian tail encounters recently have been identified, also (Scarf et al., 1983). The recurrence of the extended tail signature can be understood in terms of quasi-periodic expansions and contractions of the tail resulting from interaction of the tail with the pressure wave structure that dominates the solar wind at heliocentric distances greater than a few AU (Burlaga, 1983; Lepping et al., 1983).

It is possible to estimate the probability that both V2 and Saturn were within Jupiter's magnetotail during the 4 1/2 day Saturn encounter period based solely on prior and subsequent Jovian tail encounters, realizing that the tail encounters occurred quasiperiodically, i.e., approximately every 25 days according to autocorrelation analysis (Lepping et al., 1983; see also Kurth et al., 1982b). Figure 2 displays the 1981 intervals of V2 tail observations as a function of solar rotation (SR), where day 007 of 1981 was arbitrarily chosen as SR day 1 for display purposes; the pre-Saturn intervals are taken from Lepping et al. (1983), and the two post-Saturn intervals were provided by F. Scarf and J. Sullivan (private communication). Although the bars denoting the respective tail encounters are shown as continuous for simplicity, the actual detection of a tail signature was sometimes intermittent. However, the tail was observed for some significant portion of each day encompassed by the bars.

The period during which V2 traversed the Saturnian magnetosphere is labeled SATURN and extended from calendar day 237, hour 10, to the end of day 241. At the bottom of the figure is a histogram which is a composite of the 83 days on which the tail was detected, as shown in the top part of the figure and quantized to whole days. The broadness of the distribution is obviously due to several factors: (1) the encounters were not strictly periodic, i.e., the expansions and contractions of the Jovian extended tail apparently were in response to corotating solar wind pressure structures (Lepping et al., 1983), and the latter showed some variability in position and size from rotation to rotation; (2) most of the encounters were of long duration (7 of them were longer than 7 days); and (3) spacecraft motion across the Sun-Jupiter meridian plane must cause some smearing. With regard to the third point, however, there is no discernable temporal trend in the occurrence pattern, so we have assumed that changes in spacecraft position can be ignored in estimating the probability that the Saturn encounter occurred during a tail encounter. This is consistent with assuming that the tail was encountered primarily because of its extensive lateral expansion rather than bulk displacement as argued by Kurth et al. (1982b) and Lepping et al. (1983).

In order to generate a probability estimate, we regard the histogram in Figure 2 as a probability distribution and assume that the probability that a Jovian tail event will occur somewhere in the interval between the jth and kth days in the solar rotation period is given by the area under the histogram between and including the jth and kth days, normalized by the total area under the curve (N_T = 83):

$$P_{jk} = \sum_{i=j}^{k} \frac{N_i}{83}$$

In this manner we can compute a "probability of occurrence" for each of the actually-observed tail event periods, with the understanding that each period was used already to generate the distribution. Thus to the extent that the computed probabilities depend on a distribution formed by the superposition of all the individual event periods, each estimated probability is an approximation. There are probably a sufficiently large number of events that this approximation is justified for the purpose here, though not enough to justify a hypothesis on the true shape of the distribution of the parent population in view of the large amount of variability from rotation to rotation. The 13 events shown in Figure 2 thus have probabilities ranging from 0.024 to 0.81, with an average occurrence probability of 0.34 (σ = 0.28) for a "typical" single solar rotation during the overall tail observation period.

Similarly, this method can be used to estimate the probability that a tail encounter occurred between the beginning and end of the Voyager 2 encounter with Saturn. This yields P_{SAT} = 0.12, which is only a factor of 2.8 less than the average of the probabilities for the actual events and within one sigma from the average. For comparison, we also compute a probability for each of 25 possible 5-day intervals (slipping by one day for each), and these are averaged to give the average probability of occurrence during a randomly selected 5-day period. For this we obtain P_5 = 0.20, intermediate between that estimated for the Saturn period and the average for actual Jovian tail periods. The value obtained for Saturn (P_{SAT} = 0.12) is relatively lower because it encompassed the rising slope portion of the histogram, and the histogram is quite broad. However, it is also noteworthy, and of greatest significance, that it is only a factor of ~3 lower than the average or "typical" tail event and higher than many of the lower probabilities, of which the lowest was 0.024.

On the basis of the foregoing probability estimate plus the Voyager

PLS results obtained in the statistical ram pressure study, the recent discovery of nonthermal continuum radiation at Saturn by V2 (and by V1 upon re-examination) by Kurth et al., (1982a) and the close proximity in time of V2 Jovian tail encounters to the Saturn encounter, Saturn's immersion in Jupiter's tail at the time of spacecraft encounter seems quite plausible. It readily explains the unusually expanded state of the magnetosphere that apparently lasted ∽4-1/2 days, which is only slightly greater than the average duration (∽3 days) of the five most distant Jovian tail sightings (e.g., events 6, 7, 8 of Lepping et al., 1983, plus the two post-Saturn events of Scarf et al., 1983). Additional support for the probability of such an interaction has been provided by the detection of dramatic decreases in the intensity of Saturn Kilometric Radiation (SKR) observed on V2 during the 4-month period prior to the V2-Saturn encounter. These features have been interpreted as the radio signatures of successive Saturn immersions in Jupiter's distant tail (Desch, 1983). A similar decrease occurred during the passage of V2 through the Saturnian magnetosphere.

An immersion of Saturn's magnetosphere in Jupiter's tail could, at least during the beginning and ending phases, cause complex pressure gradients along its boundary due to a probable pressure gradient of the tail cross-section impinging on the magnetosphere. This effect might very well have been responsible for the unusually large number of outbound MP crossings (17) observed by V2 (Bridge et al., 1982). Under such circumstances the MP is not likely to maintain a simple shape described by a parabola of revolution, as in Figure 1, but would probably consist of complex nonuniform bulk and wave motions providing some of the multiple crossings. This will be discussed in more detail in a later section.

Magnetic Field Configuration in the Outer Magnetosphere

Dayside - Saturn has been found to have a relatively simple magnetic field structure in its outer dayside magnetosphere. The field topology there was characterized by P11 investigators as consistent with expectations for a dipole field compressed by the solar wind (Smith et al., 1980a, b). These observations were corroborated by the Voyager magnetometer measurements (Ness et al., 1981, 1982).

On crossing the MP inbound, these spacecraft observed the field to turn steeply southward, which is the direction of the planetary field at the equator (Acuña and Ness, 1976; Smith et al., 1980a). No evidence was found in the outermost dayside magnetosphere for the presence of an equatorial current sheet such as that observed inbound at Jupiter. However, observations consistent with the existence of a plasma sheet extending to at least $16R_S$ have been reported by Frank et al. (1980), Bridge et al. (1981, 1982; and Sittler et al. (1983), and a model of Saturn's planetary magnetic field which includes explicitly a modest equatorial ring current has been found to fit observations well (Connerney et al., 1981, 1983).

Figure 3a illustrates the predominantly southward nature of the magnetic field as observed on the inbound passes of V1 and V2, respectively (Ness et. al., 1981, 1982). Shown in the figure are hourly averaged vector fields for both spacecraft projected on the $X_{sm} - Z_{sm}$ plane, where the coordinate system is the planetocentric solar magnetospheric (sm) system, with X_{sm} toward the sun, Z_{sm} positive northward and oriented such that the planetary magnetic dipole axis, assumed in this case to be coincident with the rotation axis, lies in the $X_{sm} - Z_{sm}$ plane, and Y_{sm} completing the right-handed system. With no appreciable angular offset (<1°) between Saturn's magnetic dipole and rotation axes (Connerney et al., 1982), the SM coordinates comprise a fixed system at that planet. The magnitudes of the field components shown in Figure 3 are scaled logarithmically as indicated. The intersections of the respective model MP's based on actual inbound MP crossings, and where cylindrical symmetry was assumed, are also shown to illustrate differences in MP location at the respective encounters.

The initial (left-most) six hourly-averaged vectors shown for V1 represent essentially the total observed magnetic field, i.e., the field was almost perfectly southward during that period, consistent with the relatively quiet condition of the solar wind predicted for the early part of the encounter from V2 solar wind observations (Behannon et al., 1981b). In the case of V2, a more compressed MP on entry (at 0700 UT of day 237) was observed, as illustrated in Figure 3a, and the hourly-averaged data show that the field was less steady and not as totally southward-directed as found by V1, having substantial eastward and sunward components (Ness et al., 1982).

During hour 10, at a radial distance from Saturn of ~15 R_s, the field began rotating such that the eastward component was reduced, and the sunward component grew to a magnitude comparable to the southward component. The rotation continued until hour 16. This change was interpreted as a relaxation and general expansion of the magnetosphere at this time (Ness et al., 1982). Significant changes were also noted in the energetic particle proton and electron fluxes, with at first an order of magnitude increase in the fluxes as well as increased variability, followed by a factor of 40 decrease in both fluxes at a distance of 15.5 R_s (Vogt et al., 1982). It was concluded by the latter investigators that external conditions can have a major influence on the energetic particle fluxes in the outer magnetosphere of Saturn. Continuing our speculation that Saturn may have become embedded in the Jovian magnetotail during the V2 encounter, we postulate that probably it was during hour 10 of day 237 that the sunward Saturnian MP first began to cross the boundary of Jupiter's distant magnetic tail. Alternatively, it is still conceivable that a significant solar wind ram pressure change occurred at that time, since the SKR dropout onset, an independent indicator of possible immersion in Jupiter's tail, was not observed until 24 hours later (Desch, 1983).

Magnetotail - While the existence of an extended Saturnian magnetotail was implied by the P11 measurements (Smith et al., 1980a, b), it remained for Voyager 1 to obtain direct measurements within the tail proper. V1 left the magnetosphere at a local time of 0340 and at a Kronographic latitude of ~24° N. V2 provided additional observations of the predawn region (~0500 local time) at a relatively high latitude in the opposite lobe of the tail (30° S). These observations confirmed the existence of a magnetotail at least 80 R_S in diameter at the time of the V1 encounter, expanding to ~140 R_S or more during the V2 encounter, where the cross-sectional planes cited were those containing the last observed MP. V2 observed the hourly average magnetic field in the tail to vary in a relatively smooth fashion in both magnitude and direction during the entire outbound pass (Ness et al., 1982). In contrast, V1 saw oscillations of the field, in both magnitude and direction, which were interpreted as time variations in response to changes in the solar wind and IMF (Ness et al., 1981; Behannon et al., 1981).

For purposes of comparison, hourly average vector data in cylindrical coordinates are shown in Figure 3b for both Voyager spacecraft. Model MP boundaries, based on the first outbound MP crossings and assumed to be cylindrically symmetric for display purposes, are also given. Field magnitudes are scaled logarithmically, as indicated. The figure illustrates again the great difference in the MP locations observed by V1 and V2. The V2 tail field observations are consistent with a significant expansion of the magnetosphere having occurred prior to the spacecraft entering the magnetotail. It is probable that this expansion happened at the time of the observed changes in the field during the inbound pass, perhaps in association with the initial interaction with the distant magnetic tail of Jupiter as was discussed earlier. The V1 data, on the other hand, indicate that a notable magnetospheric change took place during the outbound traverse of that spacecraft (Behannon et al., 1981). The greater average strength of the tail field as a result of a greater compression of the magnetosphere is evident in the increased length of the V1 hourly field vectors, even though V1 was at a greater distance down the tail throughout its outbound pass. Because of the high north and south latitudes at which V1 and V2 crossed the respective Saturnian tail lobes, no direct observations of the tail current sheet separating those lobes were possible.

While on the scale of one-hour averages the magnetic field observed outbound by V2 up to the point of the first outbound MP crossing was steadier than that measured by V1, higher resolution V2 data revealed a greater degree of variability in both the field near the MP and the MP position than found by V1. This will be discussed in the next section.

Detection of Plasma Flows

The V1 and V2 measurements from the region of the magnetosphere near and including the dawn side magnetopause (MP) differed substantially. The

V1 magnetometer observations outbound indicated that both the boundary location and near boundary field were relatively steady at the time of that encounter, whereas V2 measurements revealed a higher degree of variability in the same region at the time of the later encounter (see Ness et al., 1981, Figure 3; Ness et al., 1982, Figure 2; and Bridge et al., 1982, Table 1).

The steadier nature of the field and plasma in the vicinity of the MP during the V1 pass permitted identification of a period (319/~1520-1540 UT) in advance of the first outbound MP crossing (at 319/1729 UT) when the plasma characteristics observed by the PLS experiment differed significantly both from the surrounding lobe plasma and also from magnetosheath plasma. As in the case of the magnetosheath, this magnetospheric region was distinguished by a notable increase in total ion flux flowing in the antisolar direction, although the flux increase was less dramatic than that in the sheath (J. Belcher, private communication).

We identify this flux enhancement interior to the MP as boundary layer (BL) plasma. We use "boundary layer" here as a generic term. Although the spacecraft was not at an extremely high latitude (24°), the observed flowing plasma may in fact have been "mantle" plasma. Since the means for making such a differentiation at this initial stage of studying limited and complex data sets are not obvious, we shall use BL throughout with the understanding that it implies a preliminary, generic description of the observed phenomena.

In the case of the earth's magnetosphere, such layers of plasma streaming in the antisolar direction along both the high- and low-latitude dawn and dusk flanks of the magnetotail inside the MP has been observed and studied extensively (see reviews by Sckopke and Paschman, 1978, and Paschman, 1979) since first detected a decade ago (Hones et al., 1972). Typically, as measured by IMP 6 (Eastman and Hones, 1979), the terrestrial BL has an ion density which is a factor of 20 lower than that of the magnetosheath at the MP, the bulk speed is a factor of 5 lower and the ion temperature is a factor of 5 higher (Eastman, 1979). Actual values of these parameters are of course local time dependent.

In Figure 4 are V1 measurements during a 4-hour period containing both the BL interval described above and the first outbound MP crossing. Shown are the 9.6s average magnetic field magnitude B, heliographic longitude λ and latitude δ (see caption for coordinate definitions), pythagorean mean rms deviation, and plasma proton number density n_p. The plasma instrument noise level corresponds to a density of about $10^{-3} cm^{-3}$, and proton density values near that level should be considered as at the noise level. Proton flux spectra for the BL and magnetosheath plasma are compared in Figure 5. It is obvious that the spectra differ significantly in the two regions, with a high peak flux characterizing the sheath, whereas a shift toward higher energies and a greater spectral spread (and therefore higher temperature) is evident in the BL spectrum.

As indicated in Figure 4, there is also evidence of BL plasma during the interval 1650-1729 UT, just prior to the MP traversal. It is probable that the earlier (1520-1540 UT) BL observation represented the first contact with the BL plasma. Possibly some of the repeated observations of the BL and later of the MP could have been the result of surface waves on the boundary as interpreted and discussed for the earth's tail MP by Lepping and Burlaga (1979) and Paschman (1979) and for Saturn's sunward MP by Lepping et al. (1981a). In this case it is more likely, however, to have been the result of bulk motion of the boundary since the separations in time between successive MP crossings were long and irregularly spaced (see Table 1 in Ness et al., 1981). They ranged from 31 m to 2h 22m compared with the average of 23.5m, with little deviation from the average, found by Lepping et al. (1981a) for Saturn's sunward MP.

The identification of the tailward flowing plasma seen by V1 as BL is based, in addition to the occurrence of the sheath-like (but lesser) total flux enhancement, upon the following additional observations: (1) the 9.6s average magnetic field, which was magnetosphere-like, did not change direction significantly during the period; (2) the plasma in the region was very hot but with proton density a factor of 10 lower than magnetosheath values (0.01 cm^{-3} compared with 0.1 cm^{-3}); and (3) the occurrence of this hot but lower density plasma is well-correlated with an increased magnetic field RMS over 9.6s averaging intervals. A continuation of magnetic field fluctuations from the magnetosheath into the BL has been observed at Earth's MP (Eastman and Hones, 1979). It is of interest to note that there is also a feature at one kilohertz coincident with the BL interval in the plasma wave intensity data of Gurnett et al. (1981, Figure 1).

Additional evidence in support of the BL interpretation has been provided by the plasma electrons, which were measured by the PLS experiment in the energy range 10-5950 eV. The V1 electron flux spectra taken in the BL region and in the magnetosheath are similar to the ion spectra (E. Sittler, private communication). They are also similar to electron spectra taken inside and outside the MP, respectively, by the PLS experiment on V2. In contrast, the evidence for BL plasma found in the V1 ion data is not apparent in the V2 ion data. This suggests an interpretation of the V2 electron spectra from the vicinity of the MP (that were similar to those from the V1 BL plasma) as not resulting from BL plasma but rather from plasma sheet electrons (E. Sittler, private communication). There is strong evidence that plasma sheet electrons were seen all the way to the magnetospheric boundary by V2 outbound (Sittler et al., 1983). The V2 ion detectors were not appropriately oriented to detect any corotating plasma sheet flow in that region, so that lack of an ion signature was not of relevance for the plasma sheet; but there was also no clear indication of ion flow from the sunward direction inside the MP (which could have been detected), as seen by V1. While possibly the result of different solar wind conditions, it is also possible that the lack of similarity between V1 and V2 plasma observations near the MP were the result of Saturn's magnetosphere passing through the Jovian tail during the V2 encounter, resulting in a significant decrease of solar wind plasma during the tail immersion. There is plasma flowing within the Jovian tail at these distances, but it is of lower density (much lower in the "central" or "core" region) than in the solar wind (Lepping et al., 1983).

The relatively greater variability observed at the MP outbound by V2 compared with V1 observations, as evidenced by the multitude of MP crossings and more variable magnetic field and plasma conditions, could be explained by: (1) nonuniformity of the pressure profile within the Jovian tail; (2) motion of the Jovian tail in response to solar wind variations;

and (3) possible short-term contractions and expansions of the tail, causing intermittent or eventually constant reimmersion in solar wind plasma where the net pressure would be higher.

SUMMARY AND DISCUSSION

The main results, and some speculations based on them, from this study of principally Voyager magnetometer and plasma science measurements at Saturn are as follows:

1. V1 measurements lead to the conclusion that at Saturn the subsolar magnetosheath is thinner in proportion to the MP distance than at Earth. A BS to MP distance ratio of 1.11 is inferred, compared with 1.24 at Jupiter and 1.33 at Earth. However, an average value for Saturn of 1.29 ± 0.10 is obtained from combined V1, V2 and P11 boundary crossing data, where boundary locations were admittedly more variable on V2 and P11. This leads to the speculation that Saturn's magnetosphere may be less blunt than that of Earth, especially in the meridian plane profile. This will be discussed further below.

2. The observed variability in boundary positions represents the response of the Saturnian magnetosphere to external pressure variations. In the case of V2 these variations were quite large. A possible interpretation is that they represent expansions and contractions in response to the large pressure changes associated with crossing the distant Jovian magnetotail. Based on a study of a set of 13 V2 encounters with Jupiter's tail, both pre- and post-Saturn encounter, the likelihood of Saturn having been in the Jovian tail during the V2 Saturn encounter is estimated to be approximately 1/3 the average "occurrence" probability for 13 known tail "events". Because of this and other supporting evidence, we consider it quite possible that V2 and Saturn were in the distant tail of Jupiter at that time. Differences between V1 and V2 observations near Saturn should be investigated on that basis.

3. Measurements by V1 plasma science instruments and magnetometers provide evidence for the existence of an internal boundary layer or mantle

plasma at the pre-dawn MP. This interpretation is based on the presence of an enhanced flux of antisolar-directed ions, with the temperature of the flow higher than that observed in the magnetosheath. No significant change in magnetic field direction was observed in the region identified as BL, but field fluctuation levels (rms over 9.6 s intervals) were enhanced relative to levels in the lobe field but less pronounced than in the magnetosheath. The absence of a clear BL signature during the V2 outbound MP crossings may have been related to the unusually expanded state of the magnetosphere at that time and possibly the result of an encounter with the distant tail of Jupiter.

In addition to the above results, the magnetic field structure in the outer dayside magnetosphere of Saturn has been found to be consistent with that of a compressed dipole, more nearly resembling in topology the earth's outer dayside field structure than that of Jupiter. Clear evidence for the formation of a Saturnian magnetotail has been provided by P11, V1 and V2, most particularly by V1, as discussed in earlier work. On the nightside, comparison of observations by the two Voyagers shows that the magnetic structure in both the day and nightside magnetospheres undergoes marked, temporary modification as the magnetosphere responds to changes in external pressure.

The first of the summary points above warrants additional discussion. The use of the results of research in hypersonic aerodynamics to infer a relationship between shock standoff distance and body shape (in our case that of the magnetosphere) is perhaps the weakest of our conclusions. There is no doubt that the shock distance-body shape relationship exists in ideal hypersonic flows past bodies of revolution. To what extent the results are modified for obstacles lacking cylindrical symmetry is not completely clear to us at the present time. A very small amount of flattening in the vertical plane (i.e., the X_{SM}-Z_{SM} plane) relative to breadth in the transverse direction, for example, may not alter the picture significantly. We know, for example, that a sharp, wedge-shaped obstacle has qualitatively the same effect as a pointed object of revolution in having a narrow sheath at the nose. For cases in which the asymmetry is more pronounced, say if the nose shape is more blunt than spherical in the horizontal plane (i.e., the $X_{SM}-Y_{SM}$ plane) and less blunt than a sphere in the perpendicular plane, then it is possible that the profile with minimum cross-section, i.e., the most pointed profile, will dominate in determining standoff distance, although it is also possible that some type of "average" distance results. In the case of the solar wind, it is likely that the response to obstacle shape is always weighted by the influence of the magnetic field carried by the plasma (Zwan and Wolf, 1976).

Of possible relevance to these considerations are the results of the recent study by Slavin et al. (1983) mentioned earlier. Using a subset of the published MP crossing locations, both inbound and outbound, for P11 and the Voyager spacecraft, these authors have scaled the boundary positions to correct for differences in upstream dynamic pressure. The scaling relation that was applied to predict the external pressure uses the average strength of the magnetospheric magnetic field near the MP and the minimum variance orientation of the MP at the time the boundary was crossed. This scaling has been used with some success to model the dayside boundaries of the terrestrial magnetosphere (Holzer and Slavin, 1978; Slavin and Holzer, 1981). In the case of Saturn, however, much less data is available, and significant time variations occurred for a portion of the data used.

That analysis produced a model MP that is more blunt at the nose than is that of the earth. This may indeed be the case, at least primarily for the equatorial plane profile to which the analysis was applicable, but, unfortunately, valuable information in the form of the Voyager 1 average outbound MP location was ignored, because it violated a limitation of the scaling technique: it was more than one standoff distance downstream from Saturn. Since the inbound crossing points cluster in a small region near the nose of the magnetosphere after external pressure scaling, by ignoring the most tailward crossings (V2 outbound), the final shape of the MP derived by Slavin et al. depends crucially on the widely-ranging V2 outbound crossing locations (see Figure 1). Only a subset of these were used, and they were averaged to a point. The scaling of this point is suspect, because it leads to a model MP shape that is a hyperbola, more characteristic of a bow shock than a MP (and thereby not appropriate for a smooth transition to a model magnetotail boundary surface) with a focus

5 RS sunward of Saturn. With such a limited number of observations it is not clear where the focus for the MP should be, but we know that in the earth's case it is ~3.5 R_E tailward of the earth, as pointed out by Ness (1977). In preliminary Saturn MP modeling by Ness et al. (1981, 1982), the focus was fixed at Saturn, and parabolas were employed for the fitted model surfaces. A more careful scaling of the V2 outbound boundary crossings and inclusion of the V1 data in the Slavin et al. analysis would result in a notably less blunt profile for any reasonable external pressure.

Beyond the considerations addressed above, there remains also the fact that the Slavin et al. analysis tells us nothing about the shape of the MP in the vertical plane. The results of the standoff ratio comparisons described in the present paper may be telling us that there is flattening of the magnetospheric vertical plane profile. In any case, the problem is sufficiently complex that additional analysis, and possibly additional observations, will be required to predict with confidence the three-dimensional shape of the sunward magnetospheric boundary at Saturn.

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FIGURE CAPTIONS

Figure 1 Trajectories of Voyager 1 (V1) (Left side) and Voyager 2 (V2) (right side) in cylindrical coordinates, where X is positive toward the sun and X, Y, Z are orthogonal. Distances are in units of Saturn radii, R_S (= 60,330 km). For V1, model bow shock (BS) and magnetopause (MP) boundaries are given; for V2 observed average (AVE) inbound and outbound BS locations plus model MP boundaries are shown (Ness et al., 1982). The outbound "early" MP model is based on an average of the first 5 outbound MP traversals. The "last" outbound model MP corresponds in location to the last crossing observed (Bridge et al., 1982) and preserves the shape of the "early" MP.

Figure 2 Summary of pre- and post-Saturn periods during which Voyager 2 detected anomalous magnetic fields and plasma effects interpreted as evidence for immersion in the extended Jovian magnetotail. The respective time intervals during which tail was observed at least intermittently are shown as they occurred within successive solar rotation periods (of arbitrary phase), with the first calendar day of each period given at the left. The Saturn encounter interval (MP to MP) is also shown relative to the recurring tail intervals. Integral days of observed tail are summed vertically to form the histogram in the bottom panel. N_T is the total number of days under the curve (see text).

Figure 3 (a) Projection of V1 and V2 hourly average magnetic field components in the sunward Saturnian magnetosphere onto the solar magnetospheric (SM) X-Z plane, which is a noon-midnight meridian plane. Intersections of model magnetopause with that plane, assuming cylindrical symmetry, are shown. These data illustrate the initially more compressed and later more dynamical state of the dayside magnetosphere at the time of V2 inbound relative to V1 inbound.

(b) Magnetic fields measured in Saturn's magnetotail and predawn magnetosphere by V1 and V2, respectively. Hourly average data are given relative to cylndrical coordinates (see Figure 1 caption). Greater temporal variation of the field was observed during the V1 outbound pass than during that of V2, and the data show that a higher field magnitude was seen at V1 than at V2 in spite of greater distance down the tail.

Figure 4 Magnetic field magnitude B, direction angles and pythagorean mean rms measured by V1 near the tail magnetopause, MP, top 4 panels, respectively) and proton number density n_p determined from Plasma Science experiment (PLS) (bottom panel). The field direction is expressed in terms of heliographic longitude (λ) and latitude (δ) angles measured with respect to the $\hat{R} - \hat{T}$ plane at the spacecraft, where $\hat{R}$ is radially away from the sun and $\hat{T}$ is perpendicular to $\hat{R}$ and parallel to the sun's equatorial plane; λ is measured counterclockwise from $\hat{R}$ in the $\hat{R} - \hat{T}$ plane as viewed from the north, and δ is positive northward of that plane. BL delineates boundary layer plasma (see text).

Figure 5 Proton flux spectra measured by the V1 PLS instrument in the regions identified as magnetosheath (MS) and boundary layer (BL) respectively. These spectra provide evidence for higher temperature plasma in the BL.

TABLE 1

SATURN BOUNDARY OBSERVATIONS

DISTANCE RANGE (IN R_S) AND NO. OF CROSSINGS

	INBOUND		OUTBOUND	
	BS	MP	MP	BS
S/C	RANGE (NO.)	RANGE (NO.)	RANGE (NO.)	RANGE (NO.)
PIONEER 11*	24-20 (3)	17 (1)	30-40 (5)	49-102 (9)
VOYAGER 1	26 (1)	24-23 (5)	43-47 (5)	78 (1)
VOYAGER 2	32-24 (5)	19 (1)	50-70 (17)$	78-88 (7)
AVE INBOUND	25 [26]+	21 [22]+		

R_S = 60,330 KM

* WOLFE ET AL., SCIENCE, 1980.

\+ AVERAGE OVER ALL INBOUND CROSSINGS.

$ BRIDGE ET AL., SCIENCE, 1982.

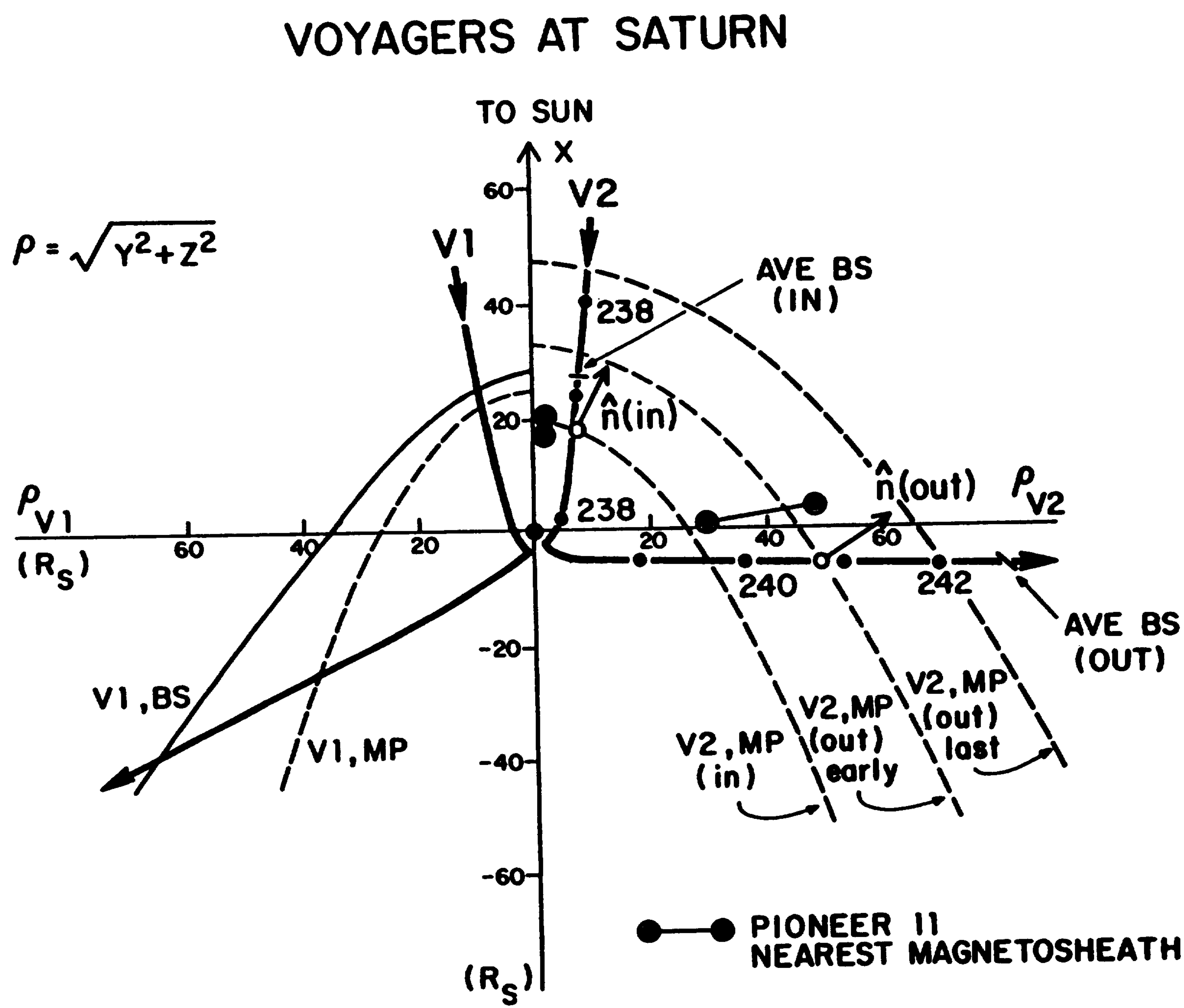

VOYAGERS AT SATURN
TO SUN
X
$\rho = \sqrt{Y^2+Z^2}$
V1
V2
238
238
AVE BS (IN)
$\hat{n}$(in)
$\hat{n}$(out)
ρ_{V1} (R_S)
ρ_{V2}
240
242
AVE BS (OUT)
V1,BS
V1,MP
V2,MP (in)
V2,MP (out) early
V2,MP (out) last
PIONEER 11 NEAREST MAGNETOSHEATH
(R_S)
60
40
20
-20
-40
-60

Figure 1

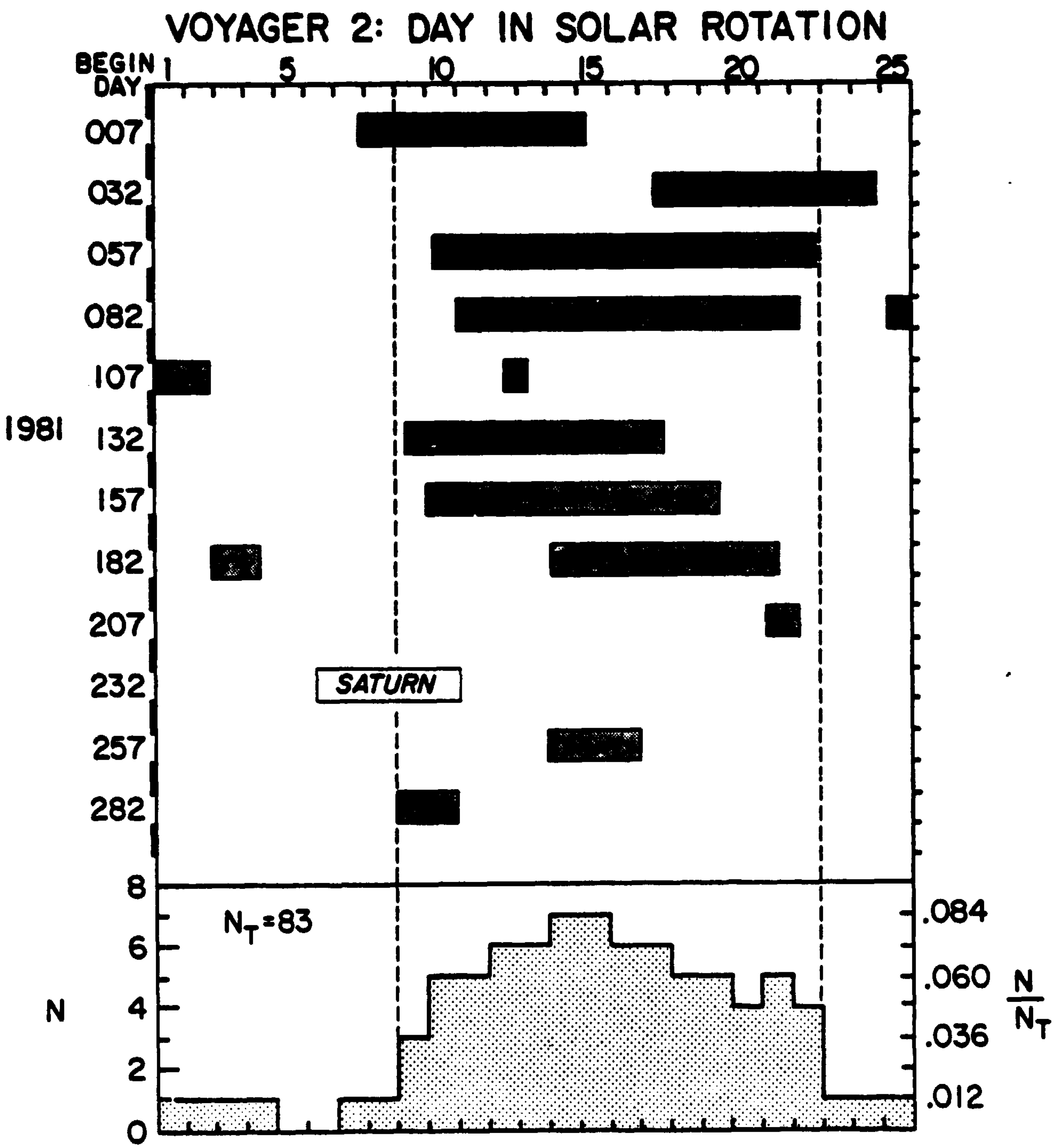

VOYAGER 2: DAY IN SOLAR ROTATION
BEGIN DAY
1
5
10
15
20
25
007
032
057
082
107
1981
132
157
182
207
232
257
282
SATURN
N_T=83
N
8
6
4
2
0
.084
.060
.036
.012
N/N_T

Figure 2

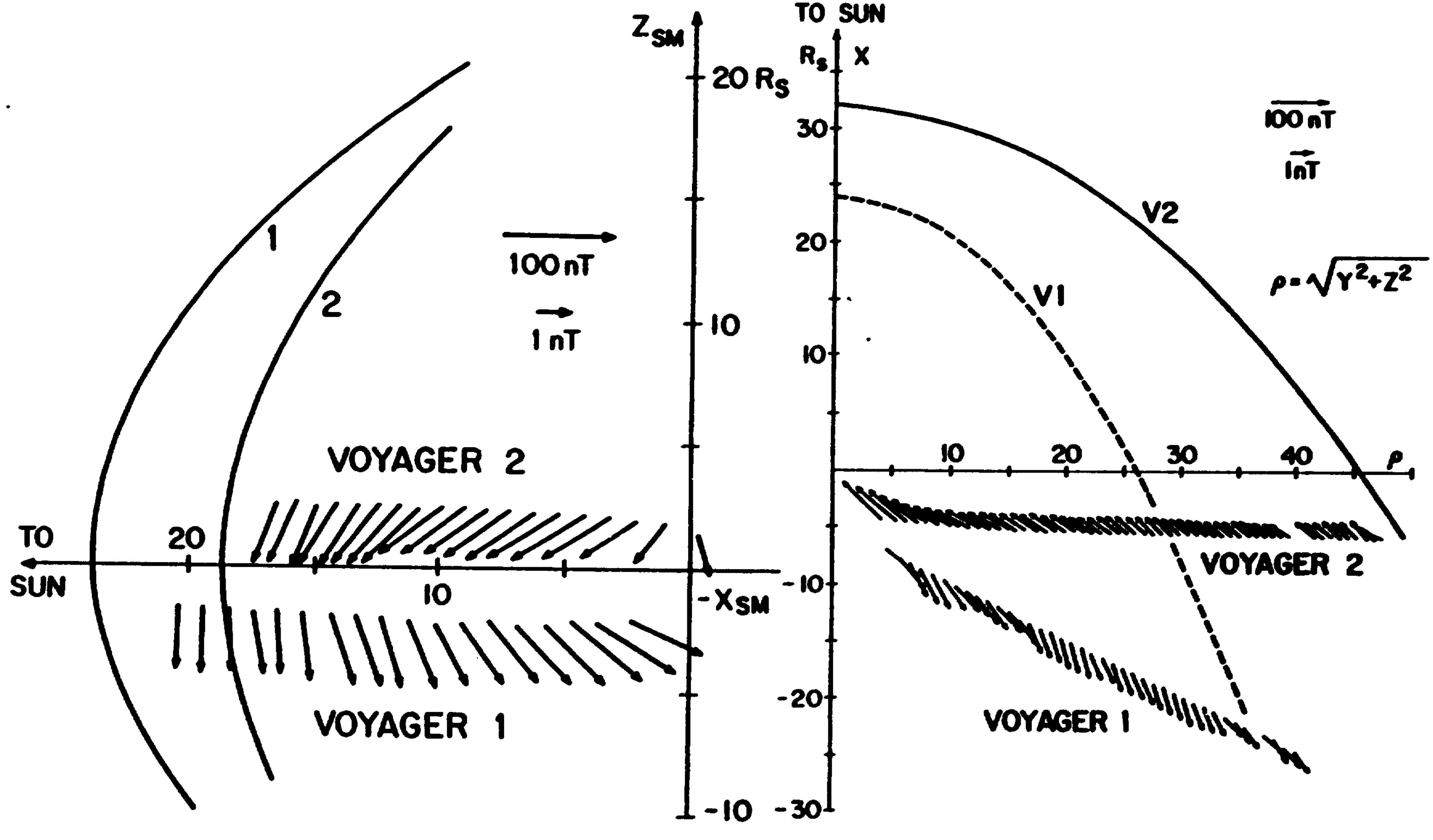
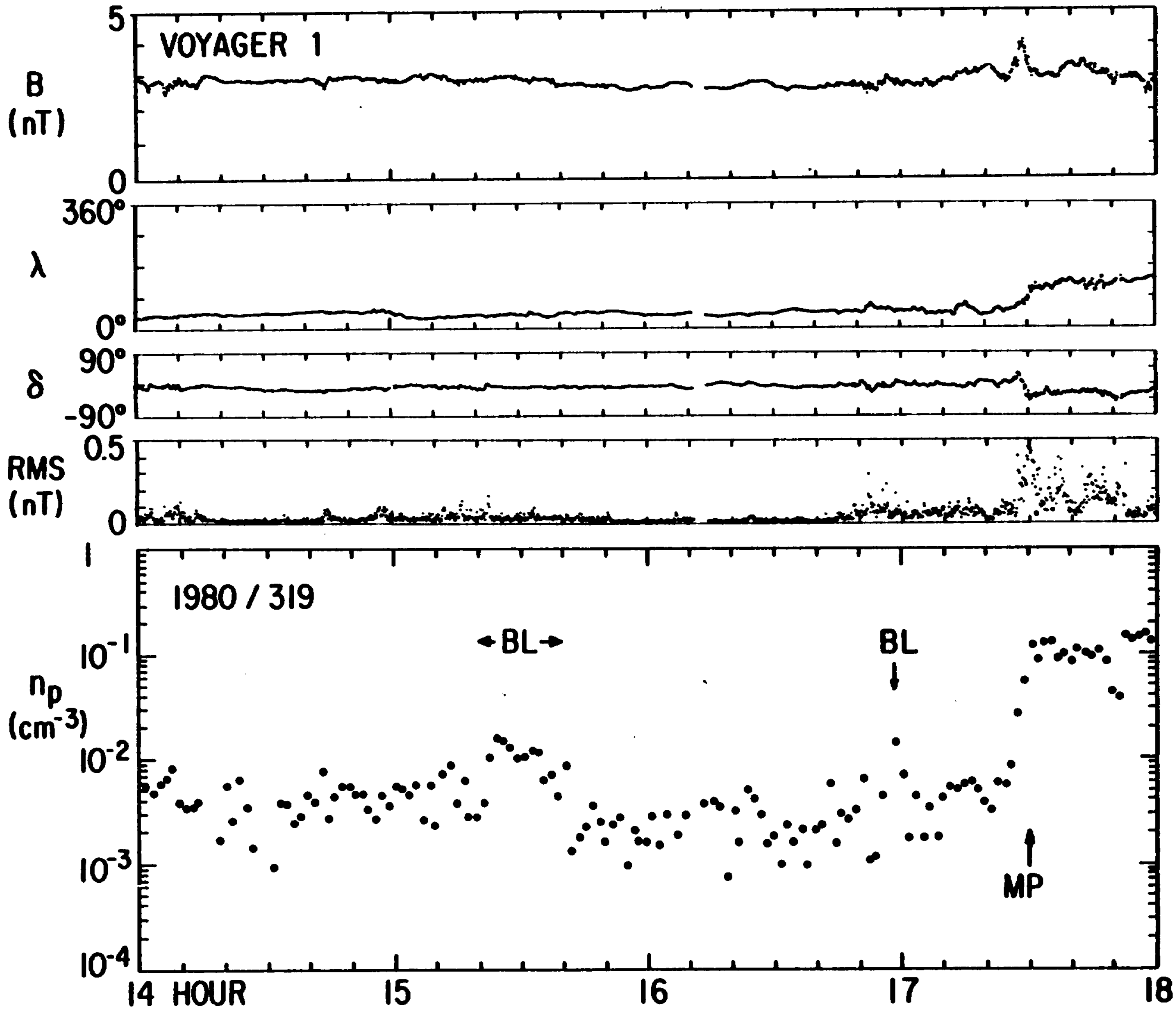

Z_SM
20 R_S
10
-10
-X_SM
TO SUN
20
10
1
2
100 nT
1 nT
VOYAGER 2
VOYAGER 1
TO SUN
R_s
X
30
20
10
-10
-20
-30
V2
V1
100 nT
1nT
ρ = √(Y²+Z²)
10
20
30
40
ρ
VOYAGER 2
VOYAGER 1

Figure 3



VOYAGER 1
B (nT)
5
0
λ
360°
0°
δ
90°
-90°
RMS (nT)
0.5
0
n_p (cm^{-3})
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1980 / 319
←BL→
BL
MP
14 HOUR
15
16
17
18

Figure 4

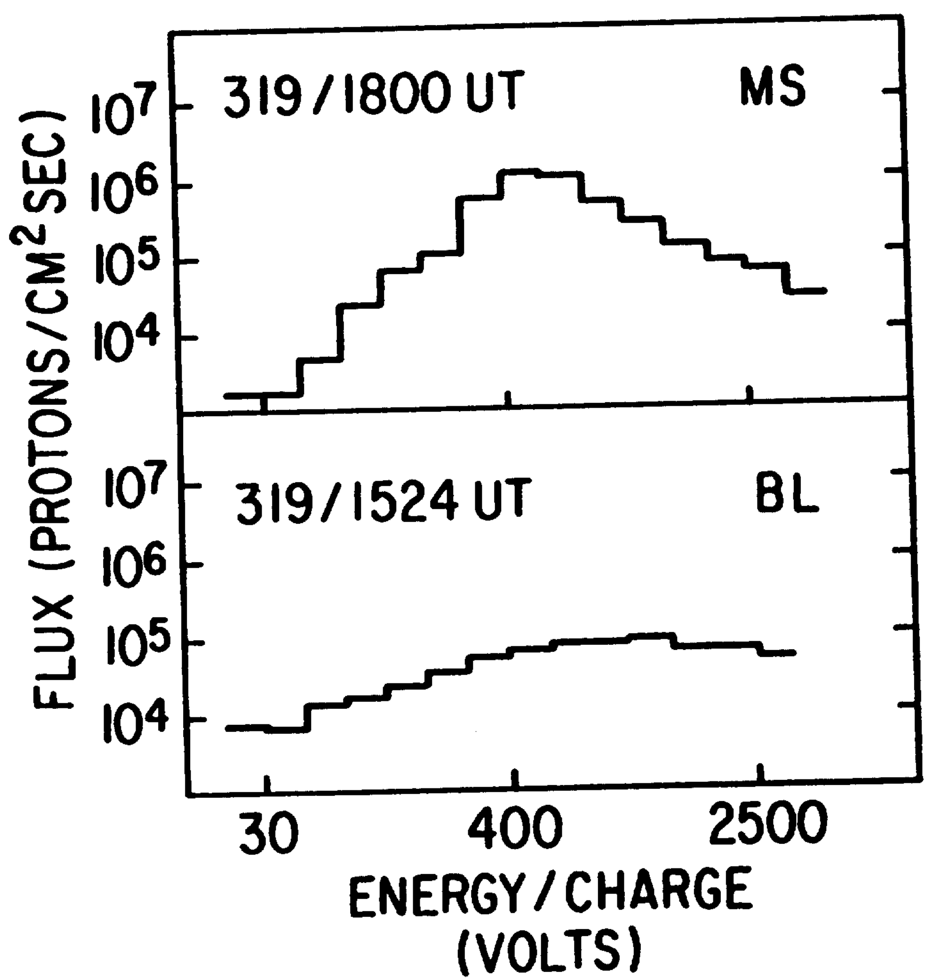

319/1800 UT
MS
319/1524 UT
BL
FLUX (PROTONS/CM² SEC)
10⁷
10⁶
10⁵
10⁴
30
400
2500
ENERGY/CHARGE
(VOLTS)

Figure 5