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Magnetopause and Cusp Observations at Neptune

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The fortuitous timing of the Voyager 2 flyby of Neptune provided a unique opportunity to carry out plasma and magnetic field measurements in a subsolar cusp region of a planet. The measured plasma parameters near the inbound magnetopause strongly suggest that a rotational discontinuity separates the magnetosheath and the high-altitude cusp region. After crossing the magnetopause, a thick layer of magnetosheathlike plasma was observed which can be accounted for by two models: (1) either a cusplike layer of stagnant plasma separated from the magnetosheath by a tangential discontinuity, or (2) or a mantlelike layer of dynamic plasma separated from the sheath by a rotational discontinuity. The plasma observations are more consistent with the mantle interpretation. Distinguishing the mantle and the stagnant cusp models is not possible on geometrical grounds because Voyager 2 crossed the magnetic polar region on the subsolar side. Inside the cusp region, there is an overall decrease in the ion density and a concurrent increase in the magnetic field strength which is consistent with a slow mode expansion fan such as is encountered in Earth's polar regions.

INTRODUCTION

The combination of a strongly tilted and offset magnetic dipole of Neptune, as was reported by *Ness et al.* [1989], creates every 16 hours the unique situation of a subsolar magnetic cusp region. The fortunate timing of the Voyager 2 encounter with Neptune offered an opportunity to study the plasma environment of this region [*Belcher et al.*, 1989]. Two current models of cusp regions, stemming from Earth measurements, are a cusp region filled with stagnant plasma separated from the magnetosheath by a tangential discontinuity and a mantle layer of dynamic plasma separated from the sheath by a rotational discontinuity [*Paschmann et al.*, 1976; *Siscoe*, 1988]. In this paper, we hope to establish which model best describes the observations at Neptune.

INSTRUMENT AND ANALYSIS

The Voyager 2 plasma science (PLS) instrument consists of four, modulated-grid Faraday cups, three of which point nearly toward the Sun, while the fourth was oriented to look into the corotational flow of Neptune's magnetosphere during the traversal of the magnetic polar region. A complete description of the instrument is given by *Bridge et al.* [1977], and the sampling scheme, which was the same as used at Uranus, is described by *Sittler et al.* [1987]. In this paper, only ion measurements are used from the "L-long" mode, which is the longest integration time mode available (0.96 s). The use of this mode is necessary because of the particularly low densities in the observed region. In this mode, the energy/charge range covered is 10-5950 V in 16 contiguous channels with $\Delta E/E \approx$ 29%. Thirteen sets of these spectra are obtained during each 12-min instrument cycle. Interference from other spacecraft instruments further reduces the number of suitable spectra for our analysis to 5 (2 on the sheath side, and 3 on the magnetospheric side) in a five proton gyroradius region around the observed magnetopause (MP) [*Ness et al.*, 1989]. To analyze the data, a nonlinear least squares fitting routine was used, which incorporates many instrumental effects [*Barnett and Olbert*, 1986]. Plasma density and bulk velocity components were obtained that best fit the data under the assumption that all observed positive ions are protons.

From the available data points, all possible combinations of data pairs were constructed from spectra points on opposite sides of the MP. After assuming a type of magnetohydrodynamic discontinuity (either tangential or rotational), one of the corresponding discontinuity relations (see below) could be used to determine the MP surface unit normal. At this stage the validity of the assumption could be evaluated by whether the remaining discontinuity relations were satisfied by this surface normal. From the data pairs, averages and standard deviations were calculated.

THE NATURE OF THE DISCONTINUITY AT THE MAGNETOPAUSE

The inbound magnetopause (MP) of Neptune was crossed by Voyager 2 on August 24, 1989, at 1800 UT, 26 R_N from Neptune [*Ness et al.*, 1989]. The crossing is identified by the rotation of the local magnetic field direction, which in this case changed by about 45°. The MP is a magnetohydrodynamic discontinuity of which the two most common types are tangential and rotational. Though other, more exotic types are

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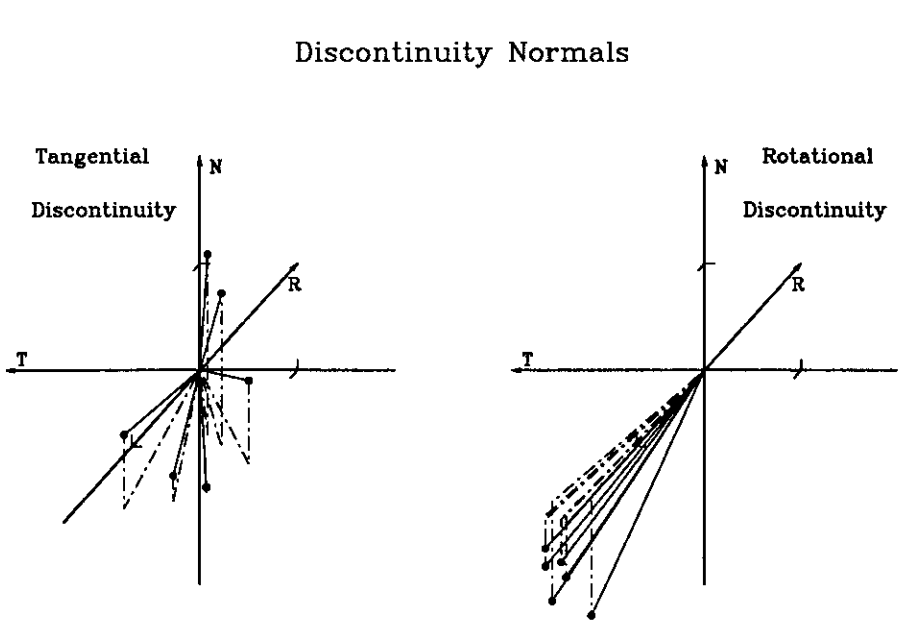

Fig. 1. Magnetopause surface unit normals calculated for the case of tangential and rotational discontinuity for each data pair used. The coordinate system is a noninertial heliographic *RTN*, where the *R* axis points away from the Sun, *N* is north out off the ecliptic, and *T* completes the right-handed system.

conceivable, they will not be considered until the more common types are completely ruled out.

The nature of the MP discontinuity also has strong implications for the geometry of the high-altitude cusp region. A tangential discontinuity would necessitate the existence of a stagnant cusp region in a typical horn shape; and a rotational discontinuity would mark a dynamic mantle layer on the southern belly of the magnetosphere. Therefore the determination of the nature of the MP discontinuity has a strong effect on the properties of the high-altitude cusp. We will return to this point in a later section.

When the directions of the discontinuity surface normals of the two common cases (tangential and rotational) are calculated (see below), we find that for a rotational discontinuity all data pairs give the same general direction (Figure 1), while if we assume a tangential discontinuity, each data pair produces a radically different orientation of the MP. This observation alone should suggest the existence of a rotational discontinuity at the MP as opposed to a tangential discontinuity. However, before coming to this conclusion, all magnetohydrodynamic discontinuity relations of a tangential and a rotational discontinuity are checked to see if any of the two types can be ruled out.

The plasma and magnetic field properties, or discontinuity relations, of tangential and rotational discontinuities are discussed by *Colburn and Sonett* [1966] and by *Landau et al.* [1984]. The special requirements of tangential discontinuity are

$$B_n \equiv \mathrm{B} \cdot \hat{\mathrm{n}} = 0 \tag{1}$$

$$v_n \equiv \mathrm{v} \cdot \hat{\mathrm{n}} = 0 \tag{2}$$

where $\hat{\mathrm{n}}$ is the unit surface normal of the MP. When condition (1) was used on both sides of the MP to calculate the direction of the discontinuity surface normal, and the validity of condition (2) was checked, the average normal flow on the magnetosheath side, normalized to the average magnitude of the plasma flow, was found to be $\bar{v}_n / \bar{v} = 0.59 \pm 0.46$. The average is taken over the values of v_n calculated for all data pairs where all v_n are normalized to the average magnitude of the plasma flow (ranging between 70 and 140 km/s) of the data pair. The requirement of zero v_n for a tangential discontinuity is slightly off the one standard deviation range of our result, which is not a statistically sufficient condition to altogether eliminate the possibility of a tangential discontinuity. On the other hand, on the magnetosphere or inner side of the MP, the agreement is much better: $\bar{v}_n / \bar{v} = -0.05 \pm 0.45$.

If we use condition (2) to calculate the surface normal and check the validity of condition (1), the result is ambiguous. On the outer side of the MP we get $\bar{B}_n / \bar{B} = 0.37 \pm 0.61$, where again the result is normalized to the magnitude of the field data ranging between 1.0 and 1.5 nT. On the inner side of the MP, $\bar{B}_n / \bar{B} = 0.57 \pm 0.72$. Though we find significant normal field components contradicting the assumption of a tangential discontinuity, our error bars are so large that we cannot with all certainty eliminate the possibility of a tangential discontinuity.

Considering next the possibility of a rotational discontinuity, the following MHD conditions are used:

$$v_n = \pm \frac{B_n}{\sqrt{4\pi\rho}} \tag{3}$$

$$[\rho] = 0 \tag{4}$$

$$[|\mathrm{B}|] = 0 \tag{5}$$

$$[v_n] = 0 \tag{6}$$

$$[B_n] = 0 \tag{7}$$

$$[\mathrm{A}_t] \equiv [\mathrm{v}_t] - \frac{[\mathrm{B}_t]}{\sqrt{4\pi\rho}} = 0 \tag{8}$$

where the square brackets signify change across the MP and the subscript t refers to the tangential component of the quantity along the discontinuity surface. Condition (3) is used on both sides of the MP to determine the direction of the surface normal, and the rest of the discontinuity conditions are checked.

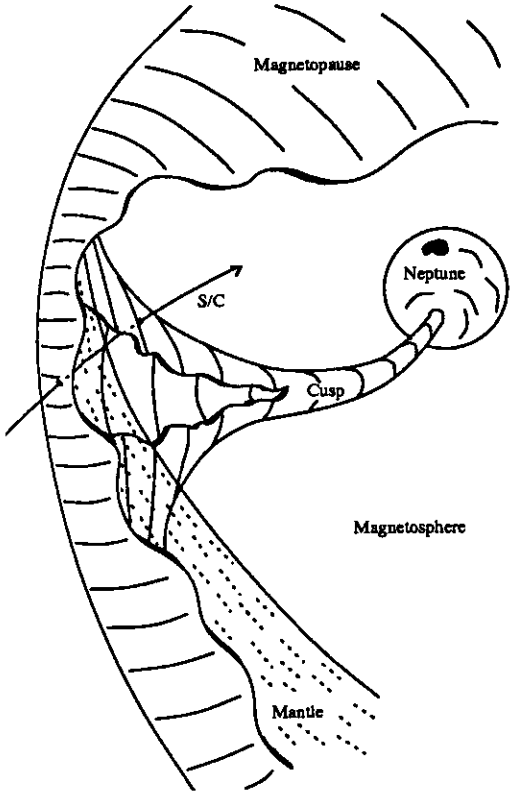

Fig. 2. Superimposed cartoon of the mantle and cusp configurations to show the similarity of the geometries from the point of view of the spacecraft.

The average change in density, normalized to the average density of 0.014-0.018 protons/cm^3, is $\overline{[\rho]} / \bar{\rho} = 0.089 \pm 0.50$. The average change in the normalized magnitude of the magnetic field is $\overline{[|B|]} / \overline{|B|} = 0.15 \pm 0.16$. The average changes in the normal velocity and magnetic field components, both normalized, are $\overline{[v_n]} / \overline{|v|} = 0.16 \pm 0.31$ and $\overline{[B_n]} / \overline{|B|} = 0.07 \pm 0.11$. That is, the range of our measurements comfortably contains the required conditions for a rotational discontinuity. Checking condition (8) in a noninertial heliographic RTN coordinate system (see Figure 1 caption), we find that $[A_t]_R / \overline{|v|} = 0.19 \pm 0.40$, $[A_t]_T / \overline{|v|} = 0.69 \pm 0.83$, and $[A_t]_N / \overline{|v|} = 0.33 \pm 0.97$. This discontinuity condition, the Walen condition [*Sonnerup et al.*, 1987], is still met inside one standard deviation, though the error bars are large. However, in the case of a tangential discontinuity, the plasma flow and magnetic fields inside and outside the MP are uncorrelated, and with Alfven velocities larger than the tangential component of the plasma flow, we would expect standard deviations of the order of 1.5 for a tangential discontinuity. Therefore even our results of the Walen condition are biased for a rotational discontinuity.

Overall, the requirements of a rotational and tangential discontinuity are all met, though not all of them with equal confidence. However, the fit is somewhat better for a rotational discontinuity than the one we have found for a tangential discontinuity, in agreement with our conclusion based on the calculated MP surface normal directions. Therefore we are fairly confident that the nature of the MP is a rotational or rotationallike discontinuity, though a tangential discontinuity cannot be completely ruled out.

GEOMETRY OF THE CUSP LAYER

The nature of the MP largely determines the type of boundary layer we will find just inside the MP. A tangential discontinuity would imply the existence of a stagnant cusp region, while a rotational discontinuity leads to the formation of a dynamic mantle [*Yang and Sonnerup*, 1977]. The geometric structures of the two possibilities are radically different. The cusp model fills the high-latitude dipole field lines with stagnant plasma in a typical horn shape (see Figure 2), while the mantle model suggests a thick layer on the southern belly of the magnetosphere connecting back to the tail regions. Unfortunately, the Voyager spacecraft crossed the region on the northern or subsolar side where the geometries are inseparably similar (see Figure 2). Therefore we cannot distinguish between the two models only on the basis of the locations of the boundaries of the cusp layer, and our geometric observations are consistent with both scenarios. The dipole axis of Neptune passed under Voyager 2 after the spacecraft left the boundary layer, which would indicate that the boundary feature is not symmetric around the dipole axis. The spacecraft left the cusp region at a much higher magnetic latitude than where it entered the region (Figure 3). This observation, however, does not rule out the stagnant cusp model, because both Earth observations and computer modeling show that the cusp regions tend to be distorted toward the subsolar point, which would make our data consistent with the model.

PLASMA PROPERTIES OF THE CUSP

Inside the boundary layer we see an overall decrease in the ion density with a concurrent increase in the magnitude of the magnetic field (see Figure 4.). This phenomenon is characteristic of a slow mode expansion fan predicted by the mantle model. However, since the stagnant cusp is turbulent and unpredictable, we cannot say if this observation is inconsistent with that model. The observed expansion fan is not unlike that measured in the Earth mantle region.

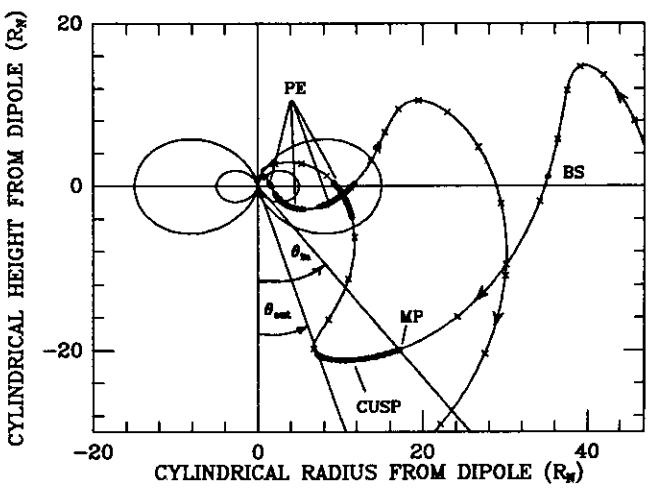

Fig. 3. Trajectory of Voyager 2 in magnetic coordinates, where the horizontal axis is the cylindrical radius from the offset tilted dipole (OTD) and the vertical axis is the cylindrical z from the OTD. The inbound bow shock (BS), magnetopause (MP), cusp, and plasma enhancements (PE) are clearly marked. The latitudinal asymmetry of the cusp is emphasized by showing the latitude extent of the cusp (θ_{in}, θ_{out}).

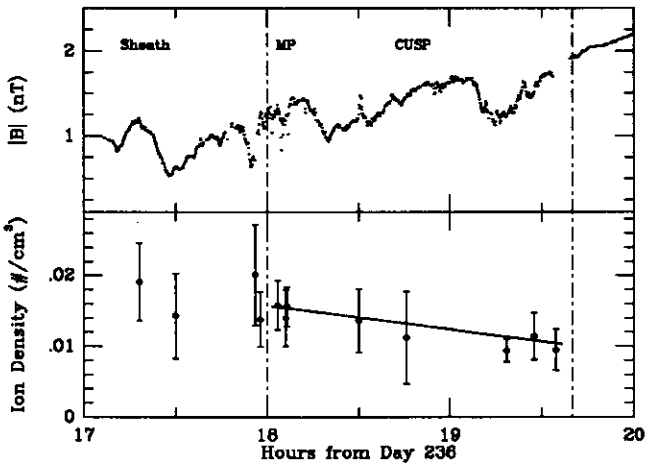

Fig. 4. The magnitude of the magnetic field and the measured ion densities in the cusp showing the characteristics of a slow mode expansion fan.

SUMMARY

The boundary layer measurements of Voyager 2 at Neptune opened the door for a firsthand observation of a subsolar cusp region. Though we cannot with all certainty determine the nature of this region, our measurements strongly suggest the existence of a dynamic mantle region separated from the magnetosheath by a rotational discontinuity as opposed to a stagnant cusp model which would necessitate the presence of a tangential discontinuity. Though the geometrical structures of the two scenarios are radically different (the stagnant cusp is in a horn shape, while the dynamic mantle is in a layer on the southern belly of the magnetosphere), unfortunately they cannot be distinguished in our analysis because of the particular trajectory of the Voyager 2 flyby. In later studies, more exotic kinds of discontinuities will be considered, such as the possibility of an intermediate shock. This understanding of the Neptune cusp region can help us to further understand the still controversial Earth polar region models.

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