Evidence of a Diffuse Magnetopause Boundary

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Observational evidence is presented to show that the magnetosphere-magnetopause boundary was diffuse during the Pioneer 8 magnetopause traversal on December 14 and 15, 1967. This boundary was characterized by proton fluxes of significantly lower intensity than those observed in the magnetosheath. In addition, the angles of flow associated with the fluxes at the boundary were more diverse than those observed in the magnetosheath. Proton energy spectra are presented to indicate the change in the spectral shape at the boundary. The observational evidence is consistent with calculations by Axford and Dryer of a viscous magnetopause boundary layer, which is a function of an anomalous nonclassical kinematic viscosity. The observational evidence presented for the diffuse magnetosphere boundary may also be consistent with Dungey's model for reconnection of magnetic field lines and an open magnetosphere.

The shape and location of the near-earth magnetopause is understood in terms of analogies with continuum gas dynamics [see review by *Wolfe and Intriligator*, 1970]. However, the detailed internal structure of the magnetopause remains uncertain [see review by *Willis*, 1971]. A number of theories have been examined in an attempt to understand the physical mechanisms involved. The hypothesis that there is a viscous interaction between the solar wind and the magnetosphere at the magnetopause was suggested by *Axford and Hines* [1961]. It was discussed further by *Axford* [1964], *Dryer and Heckman* [1967], *Faye-Petersen and Heckman* [1968], *Coleman* [1970], and *Cassen and Szabo* [1970]. *Parker* [1967] and *Lerche* [1967] examined the magnetopause from the particle viewpoint and suggested that fluctuations may be an essential feature. *Eviatar and Wolf* [1968] have examined how plasma instabilities affect the drag on the geomagnetic cavity.

Dungey [1961] suggested a reconnection model resulting in an open magnetosphere. In this model, interplanetary field lines are carried along by the solar wind and become distorted as they connect to geomagnetic field lines in flowing past the magnetosphere. The interplanetary field lines and the geomagnetic field lines are then restored to their original configuration when they reconnect downstream in the tail at the neutral point.

Measurements of the dynamic interaction between the earth and the solar wind can differ significantly, depending on the state of the magnetosphere and the interplanetary medium at the time of such observations [*Wolfe and Intriligator*, 1970]. *Cummings and Coleman* [1968] and *Freeman et al.* [1968] have reported the observations of multiple magnetopause crossings by ATS 1 when the magnetopause was greatly depressed so as to be below the 6.6 R_E distance of the synchronous equatorial orbit. *Cummings and Coleman* [1968] using magnetic field data found no evidence for the rotational discontinuity that would presumably be associated with the open magnetosphere. *Freeman et al.* [1968] using plasma data found a new component of ion flow (at ~1400 LT) immediately inside the magnetopause. This flow had characteristics that were nearly identical to the magnetosheath ion flow. The flow was paralled to the boundary in the downstream direction, and the total ion flux was almost the same as that found across the boundary in the magnetosheath. They considered this flow to be generally consistent with the flow pattern suggested by *Axford and Hines* [1961]. *Wolfe and McKibbin* [1968] used plasma and magnetic field data from the magnetopause crossing of Pioneer 6 (at $\sim$13 R_E, $\sim$1500 LT) and found an abrupt cutoff in the flux of solar-wind ions at the magnetopause. *Smith and Davis* [1970] reported on the Mariner 5 magnetic field observations at the time of the magnetopause crossing. During this crossing (at $\sim$11 R_E, $\sim$1600 LT), there were large-amplitude disturbances on either side of the boundary. They found that the magnetopause had the form of a tangential discontinuity, corresponding to a closed magnetosphere. *Aubry et al.* [1971] used Ogo 5 magnetic field and energetic-electron data to examine multiple crossings of the magnetopause (at $\sim$10 R_E, $\sim$0900 LT). They emphasized that the observed local characteristics of the boundary (as determined by both the field and the particle measurements) were extremely variable and did not fit any steady open- or closed-magnetosphere model.

In this paper we discuss the plasma data obtained during the Pioneer 8 magnetopause crossing. Unlike the crossings discussed above, this crossing occurred at a large geocentric distance in the downstream region of the magnetosphere.

OBSERVATIONS

Pioneer 8 was launched on December 13, 1967, into a heliocentric orbit. Its near-earth trajectory is shown in Figure 1. The location of the magnetopause boundary in the sketch is based on the observations obtained on Pioneer 8 on December 14 and 15, 1967. As is indicated, the spacecraft encountered the magnetopause boundary at a distance of 35–40 R_E downstream from the earth in the antisolar direction. At this time (when $X_{se} \sim -40$ R_E), $Y_{se} \sim -20$ R_E, and $Z_{se} \sim -5$ R_E. Plasma data are presented from the Ames Research Center solar-wind plasma spectrometer. This instrument is a truncated hemispherical multicollector curved-plate electrostatic analyzer [*Intriligator et al.*, 1969], and it measures both electrons and ions.

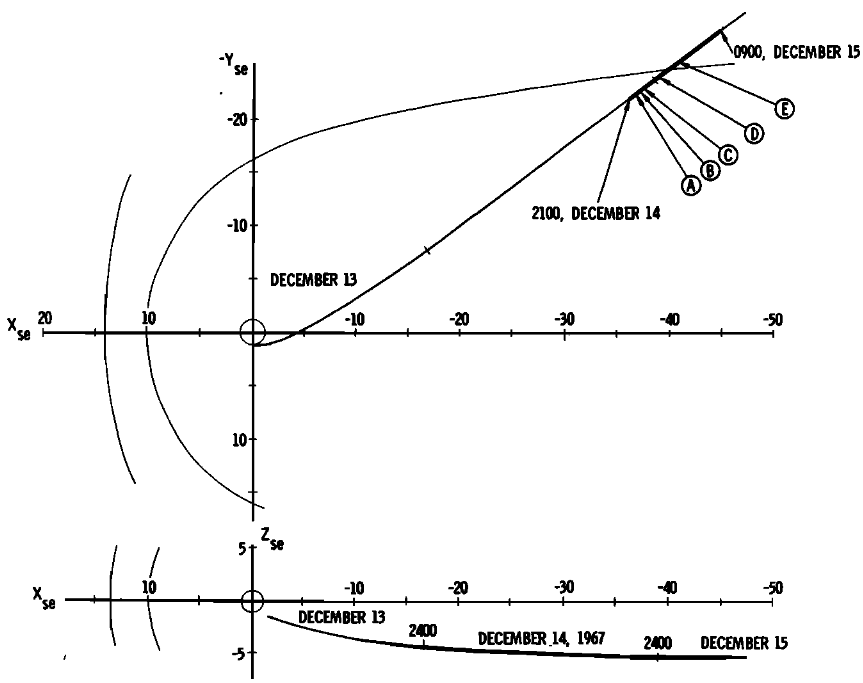

Fig. 1. Pioneer 8 outbound trajectory. Data from 2100 UT on December 14 to 0900 UT on December 15, 1967, are discussed in detail. Points A through E indicate the location of the spacecraft when specific measurements were acquired (see Figures 2 and 3).

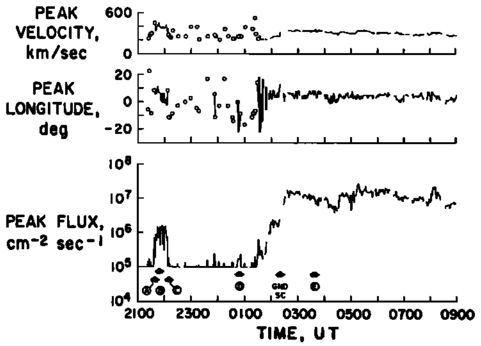

Fig. 2. Plasma parameters obtained from 2100 UT on December 14 to 0900 UT on December 15, 1967. (Bottom) The peak proton flux measured in the energy (energy per unit charge, E/Q) channel that measured the peak. (Middle) The azimuthal angle of flow associated with the peak flux. (Top) The velocity associated with the peak flux. Circles represent discontinuous data points.

Ions are measured in the energy range of 150–15,000 volts. In this paper, only the proton measurements will be discussed.

Figure 2 indicates the changes in several of the measured plasma parameters from 2100 UT on December 14 to 0900 UT on December 15, 1967. The bottom graph shows the peak proton flux measured in the energy (energy per unit charge, E/Q) channel that measured the peak. The middle graph shows the azimuthal angle of flow associated with the peak flux, where positive values correspond to flow from the west of the sun. The aberration due to heliocentric spacecraft motion has not been removed. The top graph indicates the velocity associated with the peak flux.

The graph of the peak flux indicates that the measurable flux was at or below background level until ~2139 UT (point A), when it began to rise. The plasma flux remained above threshold values until ~2210 UT (point C). Then for several hours the flux levels were depressed. At ~0048 UT on December 15 (point D), there was some measureable flux recorded, but it was not until ~0130 UT on December 15 that some longer intervals of measurable flux were again recorded. Subsequently, the more familiar flux levels and ion energy spectra associated with the magnetosheath were encountered. The magnetospheric locations of Pioneer 8 when the measurements that correspond to points A through E were acquired are indicated in Figure 1.

The graph of the peak longitude indicates that the angle of flow associated with the peak flux was varying widely between ~2139 UT on December 14 and ~0200 UT on December 15, when it finally settled down and became more regular. Similarly, the graph of the peak velocity indicates that the velocity associated with the peak flux was varying widely between ~2139 UT on December 14 and ~0130 UT on December 15, when it became more steady.

In Figure 3 the bottom graph is the same as the bottom graph in Figure 2, and it shows the peak proton flux measured in the energy channel that measured the peak. The top series of graphs give more detailed information concerning the energy spectrum of the flux and the angular distribution of the flux measured at the points A through E indicated in the bottom graph and in Figures 1 and 2. For the data corresponding to the measurement at each point the entire distribution of measured peak ion flux for each energy per unit charge step is plotted. In addition, the longitudinal angle of flow of the plasma for the peak flux of each of the E/Q steps is indicated with an arrow. For example, for point B (2148 UT on December 14) the peak flux is plotted for eleven E/Q steps. The angles of flow for the first five of the fluxes plotted are 5°, 8°, 8°, 8°, and 5°, respectively. The fifth flux value is the maximum value recorded in the E/Q spectrum, and so this value ($\sim 10^6$ ions cm^{-2} sec^{-1}) appears in the peak flux plot in the bottom graph and in Figure 2. The angle of flow associated with this value (+5°) appears in the peak longitude plot in Figure 2, and the velocity corresponding to this E/Q step (~400 km sec^{-1}) is shown in the peak velocity graph in Figure 2.

The data plotted in Figure 3 indicate that at 2139 UT (point A) the flux levels were depressed, measurable fluxes were recorded in only four E/Q channels, and the angles of flow associated with these fluxes were varying. After 9 min (point B, 2148 UT) the measured flux levels were considerably higher, the energy distribution function had broadened so that measurable fluxes were recorded in eleven E/Q channels extending up into the higher energy range (1000–2000 volts), and the angles of flow associated with the fluxes were steadier. At 2210

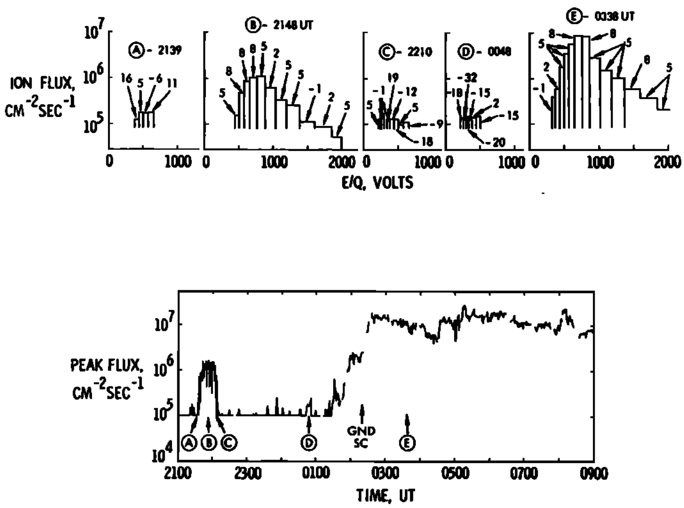

Fig. 3. The energy and angular distribution of plasma at five specific times. (Bottom) Same as the bottom graph in Figure 2. It shows the peak proton flux measured in the energy (energy per unit charge, E/Q) channel that measured the peak. (Top) More detailed information concerning the energy spectrum of the flux and the angular distribution of the flux measured at the points A through E indicated in the bottom graph and in Figures 1 and 2. See text for a more complete description of the quantities shown in the top series of graphs.

UT (point C) the measured flux levels were depressed, they were recorded only at relatively low energies (~200 to ~600 volts), and the associated angles of flow were widely varying. At 0048 UT on December 15 (point D) the measured flux levels were low, the energy distribution was relatively narrow (~200 to ~500 volts), and the associated angles of flow were again varying. At 0338 UT (point E) the more typical magnetosheath plasma was observed, characterized by higher flux levels, a broad energy distribution (~300 to 2,000 volts), and steadier angles of flow.

To examine in more detail the extent of the various regions associated with points A through E discussed above, Figure 4 shows some of the individual ion energy (E/Q) spectra. The curves in these spectra are the envelopes of the histogram-type spectra similar to those plotted in the top series of graphs in Figure 3. An ion energy (E/Q) spectrum is obtained every 60 sec. To make each individual spectrum as clear as possible, we have plotted alternate spectra (one spectrum for every two min). In Figure 4*a* the spectra from ~2131 to 2228 UT on December 14, 1967, are plotted. The first three spectra plotted indicate that the flux levels were depressed. From ~2137 to ~2206 UT the spectra are more enhanced. In Figure 4*b* the spectra from ~0145 to 0329 UT on December 15, 1967, are plotted. It is clear that the flux levels and the shape of the curves are varying from 0145 to ~0235 UT. From ~0235 to 0329 UT they are more steady and more similar to the familiar magnetosheath spectra.

DISCUSSION

The observations presented above indicate that, as Pioneer 8 traversed the region of the magnetopause at a large geocentric distance from the earth in the downstream direction, it encountered at least four regions of diffuse plasma flux: at ~2139 UT on December 14 (Figure 3, point A); at ~2210 UT on December 14 (Figure 3, point C); at ~0048 UT on December 15 (Figure 3, point D); and at ~0154 UT on December 15 (Figure 4). These regions were characterized by depressed flux levels, narrow plasma energy distributions (possibly the result of depressed flux levels), and widely varying angles of flow.

Pioneer 8 also encountered the more familiar magnetosheath flux at ~0338 UT on December 15 (Figure 3, point E), possibly previously at ~2148 UT on December 14 (Figure 3, point B), and at ~0230 UT on December 15 (Figure 4).

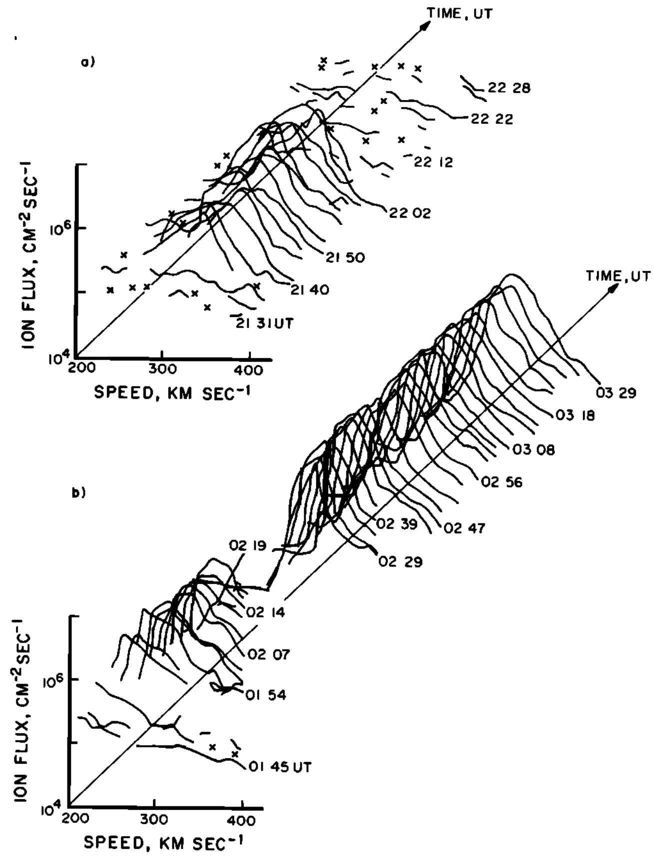

Fig. 4. Individual ion energy (energy per unit charge, E/Q) spectra. One spectrum is acquired every 60 sec. Only alternate spectra (i.e., one spectrum for every 2 min) are plotted so that each curve is more discernible. Crosses indicate isolated data points. (a) Spectra from 2131 to 2228 UT on December 14, 1967. (b) Spectra from 0145 to 0329 UT on December 15, 1967.

These regions were characterized by high flux levels, broad plasma energy distributions, and steady angles of flow.

If the diffuse plasma flux observed is associated with the magnetopause boundary itself, it implies that downstream in the magnetosphere on this occasion the boundary layer was extremely thick. *Willis* [1971] reviews the observations that imply that the boundary thickness is of the order of 100 km. Whether Pioneer 8 was traversing the spatial extent of a stationary boundary or whether it was traversing the boundary while the boundary was fluctuating back and forth, the observations of the boundary layer made by the spacecraft would imply a boundary thickness greater by several orders of magnitude than 100 km. For example, the observation of two consecutive ion energy (E/Q) spectra (a spectrum is measured every 60 sec) with an associated flow velocity of 200 km/sec (Figure 2, top) implies a boundary thickness of 12,000 km. It is conceivable that the boundary diffusion region could be thinner; however, this could only be the case if the boundary motion were synchronized to the cycle time of the plasma instrument, which seems highly improbable.

One should note that the diffuse plasma flux observed by Pioneer 8 downstream at a large geocentric distance from the earth is quite different from the flux inside the plasma boundary reported by *Freeman et al.* [1968]. The flux they reported (at 6.6 R_E, ~1400 LT) was extremely similar to the plasma flux they measured in the magnetosheath. The plasma flux they measured inside the boundary (as determined from magnetometer data) was characterized by the same flux levels and angles of flow as the magnetosheath flux they measured on the outside of the boundary. Therefore the diffuse plasma flux observed during the magnetopause traversal of Pioneer 8 is very different from the flux *Freeman et al.* [1968] observed.

The Pioneer 8 observations presented above are consistent with the fluid treatment of a viscous boundary layer (i.e., the magnetopause). As the spacecraft enters the region of reduced flux at A, the magnetopause may move outward away from the spacecraft at C and return roughly at D; the magnetopause is finally and unequivocally penetrated at E. The observation of an inferred boundary layer thickness greater by several orders of magnitude than 100 km is consistent with the *Dryer and Heckman* [1967] and the *Faye-Petersen and Heckman* [1968] computations of a thickness at a downstream distance of ~ 40 R_E of about 0.8 R_E. The observed flux levels and flow angles of the near-earth magnetopause detected by *Freeman et al.* [1968] at ~ 1400 LT are also consistent with the *Dryer and Heckman* [1967] prediction of ~ 0.1 R_E for the thickness at that position. Here the magnetopause may be associated with the turning and reverse flow of the magnetospheric convection current [*Axford and Hines*, 1961].

The observation of the variation of flux from the depressed level at A to the high level at E is particularly important in evaluating the various boundary layer hypotheses. The depressed flux level could be a sample of the lower flux well within the boundary, whereas the higher flux level is indicative of the outer 'free-stream' value in the magnetosheath adjacent to the boundary. Similarly, the widely varying angles of flow within the regions A, C, and D could be indicative of the random motion symptomatic of the turbulent momentum transfer taking place as part of the viscous process of energy transport into the magnetosphere. This finding would be compatible with that of the plasma instabilities discussed by *Eviatar and Wolf* [1968] on the kinetic level in which the source of the anomalous viscosity resides.

The observations of the varying flux levels and angles of flow may also be evidence of the open magnetosphere suggested by *Dungey* [1961]. If this were the case, the geomagnetic field lines would be connected to the interplanetary field lines during some of the time of the encounter. For example, the diffuse flux levels and widely varying angles of flow at A, C, and D could be evidence of field-line merging. It is hoped that simultaneous magnetic field data from the Pioneer 8 magnetopause traversal may soon become available so that this possibility can be explored more fully.

At least two general classes of physical phenomena may be considered as responsible for the observations: the fluid concept of a magnetohydrodynamic viscous boundary layer and the open-magnetosphere concept devoid of any viscosity. A third alternative is also possible: a combination of these two concepts wherein viscosity and resistivity are present, as is discussed by *Cassen and Szabo* [1970], together with field lines, which reverse themselves (indicative of merging), and with varying flow angles.

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