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MAGNETOSPHERIC PLASMA FLOW AND THE NATURE
OF THE MAGNETOSPHERIC BOUNDARY LAYER

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ABSTRACT

Bulk flow of plasma in the outer magnetosphere has been studied using measurements of protons ($30 \text{ eV} < E_p < 30 \text{ keV}$) made with electrostatic analyzers on the Vela satellites in circular orbits at geocentric distance, $r \sim 18 R_E$. The flow is detected, and its velocity is measured by the spin modulation it causes in the response of the analyzers on the rotating (64-second period) satellites. Very rapid flow of plasma in the magnetotail plasma sheet occurs during magnetospheric substorms. As the plasma sheet thins early in a substorm expansion phase, bulk flow in the anti-earthward direction at several hundred kilometers per second is sometimes detected, possibly indicating the formation of a neutral line at $r < 18 R_E$. The plasma that re-inflates the plasma sheet late in a substorm is observed to be flowing earthward at speeds as great as $\sim 1000 \text{ km/sec.}$, suggesting that the neutral line is re-established at $r > 18 R_E$ at that time. As the satellites pass from the magnetotail to the magnetosheath, they traverse a region, the boundary layer, whose thickness ranges up to a few thousand kilometers. The boundary layer plasma has a temperature similar to that of the magnetosheath plasma, but its number density and bulk flow speed are substantially less than those of the magnetosheath plasma. It is suggested that the boundary layer is the magnetic projection of the dayside cusp and is a site of energy and plasma transfer from the magnetosheath into the plasma sheet.

MASTER

INTRODUCTION

The magnetosphere is the product of a dynamic interchange of energy and plasma between the solar wind on the one hand and the earth's immediate magnetic environment on the other. That this dynamic interchange involves large-scale motions of plasma, particularly in the outer magnetosphere, has been widely recognized; the occurrence of such motions is a basic premise in nearly every theory of the magnetosphere. Until quite recently, however, the bulk motions of plasma in the outer magnetosphere had to be inferred from indirect evidence, e.g., measurements of ionospheric electric fields and observations of motions of auroral forms and of barium ion clouds.

Now these bulk motions of plasma have been more directly determined through the directional anisotropies they cause in the flux of plasma protons. Instruments on rotating satellites reveal the proton flux anisotropy as a spin modulation (with one peak per rotation) of their responses (Hones et al., 1972; Prakash, 1972; Hones et al., 1973b). Modulation of this type clearly cannot be due to anisotropic pitch angle distributions of the proton flux with respect to the magnetic field, for such distributions would be evidenced by modulations with an even number of peaks per rotation.

This paper is a report of the measurements of plasma flow made in this way by the Vela satellites in the magnetotail plasma sheet and in the magnetotail boundary layer. The reader is referred to Hones, et al. (1972, 1973b) and to Akasofu, et al. (1973) for more complete reports of these measurements. These more direct determinations of the bulk flow of plasma in the outer magnetosphere substantially strengthen the observational base

upon which theoretical ideas concerning such problems as plasma entry into the magnetosphere and the nature of magnetospheric substorms can be founded.

DESCRIPTION OF EXPERIMENT

The plasma measurements to be discussed here were made with hemispherical-plate electrostatic analyzers on the Vela satellites, in circular orbits at geocentric distance, $r \sim 18 R_E$. We shall be concerned primarily with energy spectral measurements of proton fluxes in the energy range ~ 30 eV to ~ 30 keV made by these instruments. The analyzers have fan-shaped acceptance solid angles which are centered in the rotational equatorial planes of the rotating (~ 64 -second period) satellites. The long dimension (~ 100 degrees) of the fan is parallel to the rotation axis and the narrow dimension (~ 3 degrees) is perpendicular to this. A complete energy spectrum (at 20 to 24 logarithmically-spaced energy levels) is measured every four seconds (every 22.5 degrees of rotation) when the satellites are operated in the real-time (high bit-rate) mode. More detailed descriptions of these instruments have been given by Montgomery et al. (1970), by Bame et al. (1971) and by Hones et al. (1972).

The central topic of this paper is the bulk flow of protons (and thus, essentially, of plasma) measured by the spin-modulation that the flow causes in the response of the analyzers on the rotating satellites. Having only a single, equatorially situated plasma detector, each Vela satellite measures something approximating the component of the proton flow velocity perpendicular to its axis of rotation. (See Hones et al. 1972, for a more detailed description of the method of interpretation of the observations.)

OBSERVATIONS

A. Flow of Plasma in the Plasma Sheet

The most striking feature of the flow of plasma in the plasma sheet is the very high velocity in the sunward (approximately earthward) direction that is encountered as the plasma sheet thickens (or recovers) late in a substorm. Figure 1 shows magnetograms from auroral zone stations, from the low polar cap station, Baker Lake and from the low latitude stations, San Juan and M'Bour, recorded on July 2, 1968. Onset of the expansion phase of a substorm at ~ 0130 UT is signified by the sharp deepening of auroral zone negative bays that started then and by the onset of a positive bay at the low-latitude, near-midnight station, M'Bour. The auroral zone bays started to recover at ~ 0145 UT. At the same time a negative bay started to develop at the low polar-cap station, Baker Lake, signifying the occurrence of a substantial poleward shift of the auroral electrojet.

Vela 4A was near the dawn side of the magnetotail, very near the neutral sheet, whose position was estimated by the formula of Russell and Brody (1967). Data from that satellite are portrayed in Figure 2. A sharp drop of the energetic electron flux ($E_e > 30$ keV) and sudden cooling of the lower energy "plasma" electrons occurred at the substorm's expansion phase onset. At ~ 0145 UT the plasma electron temperature started to increase and the energetic electron flux increased toward new higher levels. This was the onset of plasma sheet recovery, and, as is often observed, it coincided very closely with the sudden poleward shift of the auroral electrojet (Hones, et al. 1970; 1973a). Also at ~ 0145 a very

strong spin modulation of the plasma proton flux was encountered and was of such phasing with the sun signals as to indicate plasma flow toward the sun. (The rotational axis of this satellite was approximately perpendicular to the solar magnetospheric equatorial plane so that the spin modulation provided a measure of the flow vector components in this plane. Note caption of Figure 2 and see Hones, et al. (1972)). Flow velocities as great as 700 km/sec were measured. This evident, rapid flow persisted for about 10 minutes.

At the expansion phase onset of substorms, when the plasma sheet thins (i.e., the plasma intensity is observed to decrease), a flow of plasma away from the earth is sometimes encountered. An expansion phase onset occurred at ~ 1305 UT, March 5, 1968. This was marked by the sharp onset of a large negative bay at College and by the onset of a positive bay at Honolulu, both near local magnetic midnight (Figure 3). The College all-sky camera also recorded sudden brightening of auroras nearly overhead at that time. At Vela 4A, very near local midnight and $\sim 1 R_E$ from the neutral sheet, decreases of energetic electron flux and of plasma electron density began at ~ 1305 UT (Figure 4). The plasma proton flux began to decrease at ~ 1309 UT and displayed a very strong spin modulation during the decrease. The phasing of the modulation suggested a flow in the anti-sunward direction. The maximum speed of the flow was ~ 500 km/sec. Unfortunately, operation of the satellite in the real-time (high bit-rate) mode was interrupted at 1315, and further monitoring of the plasma flow became impossible. But available store-mode data show that the plasma intensity continued to decrease to background intensity levels and did not recover again until ~ 1330 UT when magnetic bay recovery began at the earth.

The two examples of plasma flow in the plasma sheet which have just been described illustrate a feature that is found generally to be true, i.e., evident spin modulation having constant phasing with the sun usually lasts only a few minutes at a time. This suggests that plasma flow in a given direction (at speeds above the 50-100 km/sec threshold of these measurements) usually does not persist for more than a few minutes at a time.

Data obtained by Vela 4B were used to determine whether there is a long term "average" pattern of plasma flow in the plasma sheet. The spin axis of Vela 4B was kept aligned along a radius vector from the earth's center by an active orientation system. Thus, when that satellite was near the center of the magnetotail, the proton flux measurements did not provide a very sensitive means for detecting plasma flow in the sunward and anti-sunward directions. Figure 5 illustrates approximately the flow vectors that would be derived from measurements made by Vela 4B at various locations in the magnetotail if an actual flow of plasma toward the sun at 100 km/sec existed throughout the tail. Note that measurements near the axis of the tail do not provide good indications of the velocity in this hypothetical flow distribution.

The vectors in the "map" of Figure 6 portray flows derived by averaging all of the proton measurements made in each $10^\circ \times 10^\circ$ box during 6 months of operation of Vela 4B. The number in each box, when multiplied by 9, gives the number of satellite rotations from which data were obtained in that box (when $k_p > 1_+$). (The absence of vectors near the center of the diagram is due to a few-week gap in data acquisition.)

No orderly pattern of plasma flow is evident in Figure 6. A similar map, compiled from data acquired with $k_p \leq 1_+$, also failed to show any systematic pattern of plasma flow. However, a map (Figure 7) compiled from flow vectors derived from groups of two or more successive satellite rotations during which the spin modulation of the proton counts was clearly evident does show a systematic flow pattern. Comparison with Figure 5 shows that the pattern of this very evident plasma flow, occurring primarily in conjunction with substorms, is consistent with flow in the general sunward (approximately earthward) direction.

B. The Magnetotail Boundary Layer

On many occasions when the Vela satellites pass from the magnetosheath into the magnetotail, or vice versa, they encounter a region, estimated to be several thousand kilometers thick, which contains plasma flowing anti-sunward but at speeds reduced from those measured in the magnetosheath. The protons and electrons in this region have temperatures comparable to those in magnetosheath plasma, but their number densities are substantially lower than those in the magnetosheath. This region is the magnetotail boundary layer. It has been detected at other distances along the magnetotail by Intriligator and Wolfe (1972) and by Howe and Siscoe (1972).

Figure 8 shows data from Vela 4B, acquired during a passage through the boundary layer at the dawn side of the magnetotail on August 10, 1967. Three types of spin modulation of the plasma proton flux are evident in the figure. From $\sim$ 0100 UT to $\sim$ 0117 UT and again from $\sim$

0139 UT to $\sim$ 0145 UT there was a moderately strong spin modulation of proton flux, with peaks seen in the sunward direction, indicating quite rapid anti-sunward flow. During these periods the satellite was in the boundary layer. From $\sim$ 0120 UT to $\sim$ 0139 UT the proton count rate was not distinctly modulated. The satellite was in the plasma sheet during that interval, a fact which is indicated also by the higher flux of energetic electrons that was encountered then. After $\sim$ 0146 UT the proton count rate was very strongly modulated. The satellite was then in the magnetosheath.

The distribution of boundary layer-like proton fluxes measured during six months of operation of Vela satellites 5A, 5B, 6A and 6B is shown by the thin lines in Figure 9. The boundary layer is encountered most frequently at large values of $|dZ_{SM}|$ at the dawn and dusk edges of the magnetotail. The Vela satellites do not reach distances $|dZ_{SM}|$ greater than $\sim 13 R_E$. Thus they do not provide direct evidence as to whether the boundary layer extends completely around the top and bottom of the tail. But extrapolation to larger $|dZ_{SM}|$ of the observations in Figure 9 suggests that it may well do so. At small $|dZ_{SM}|$, near the tail's midplane, the boundary layer is very thin or perhaps non-existent. Many passes into the tail at small $|dZ_{SM}|$ reveal an essentially instantaneous transition ($\Delta t \leq 64$ seconds) from magnetosheath plasma to plasma sheet plasma. In fact there is often seen an instantaneous reversal of plasma flow from ~ 400 km/sec anti-sunward in the magnetosheath to perhaps 200 km/sec sunward in the immediately adjacent plasma sheet.

DISCUSSION AND CONCLUSIONS

A. Plasma Sheet Flow

The most evident and most rapid flow of plasma in the plasma sheet occurs in association with substorms. The character of this flow tends to support substorm models which incur reconnection of tail magnetic field lines in the near-earth region of the tail as the mechanism responsible for substorm "breakup" (i.e., the onset of the expansive phase). This is illustrated in Figure 10. Figure 10(a) depicts a gradual thinning of the plasma sheet such as has been observed to precede the expansive phase of some substorms. The figure implies that thinning begins in response to a southward turning of the interplanetary magnetic field (IMF). The escaping plasma may flow earthward or tailward or out the sides of the tail but must do so at relatively slow speed because the Vela satellites do not detect any consistent pattern of flow at such times. In (b) the plasma sheet has grown thin enough to allow magnetic reconnection to begin suddenly somewhere between the Vela satellite (V) and the earth. Rapid tailward flow of plasma ejected from the reconnection region is observed by Vela for a short time before it is left outside the more rapidly thinning plasma sheet. Earthward of the reconnection region plasma flows rapidly earthward, causing that portion of the plasma sheet to expand rapidly (b) and (c). Reconnection continues in the near-earth region for some time (c). Tailward of this, the plasma sheet remains thin, possibly disconnected magnetically from the near-earth region which is supplying the auroral particle flux to the earth.

Late in the substorm (Figure 10(d)) the reconnection region quite suddenly and rapidly moves much farther from the earth, in associa-

tion with a rapid poleward shift of the auroral electrojet (Hones, et al. 1973a), and Vela suddenly detects the rapid earthward flow of plasma from the newly positioned reconnection region. Figure 10(d) implies that the tailward shift of the reconnection region might occur in response to a northward turning of the IMF.

B. The Boundary Layer

It is reasonable to suppose that the boundary layer is an extension, along the tail surface of field lines emanating from the dayside cusp. That is, they may be magnetosheath field lines, newly merged with the earth's field at the forward magnetopause, that have lost some of their plasma to the earth. The plasma flow velocity is reduced because of the attachment of the field lines to the earth. The boundary layer thus is the region where momentum of magnetosheath plasma is imparted to the tail, producing the tangential stress that draws out the tail. The boundary layer is also the site of the currents which confine the magnetotail to its cylindrical form.

The supposition that the boundary layer contains magnetic field lines connected to the dayside cusp is supported in a semi-quantitative way by magnetospheric model calculations portrayed in Figure 11. Magnetic field lines from the polar regions of the model were projected onto the spherical surface at $r = 18.5 R_E$ where the Vela satellites orbit. The shaded region is the projection, onto this sphere, of the dayside cusp, as identified in particle measurements made with the polar orbiting ISIS-1 satellite (Winningham, 1972). The dashed curve is the approximate

profile of the plasma sheet derived from Vela plasma measurements. The short line segments are copied from the upper right-hand quadrant of Figure 9 and are the orbit sections along which Vela satellites detected boundary layer plasma.

In the model magnetosphere used here, the last closed field line at the noon meridian is from 76° latitude at the earth and crosses the equator at $r \sim 10 R_E$. The radius of the tail is $\sim 20 R_E$ and the tail field strength is 20 gammas. It is notable that field lines in the thick dawn (and dusk) portions of the plasma sheet intersect the earth two to four hours sunward of the dawn (and dusk) meridians, in the region where the dayside cusp field lines also intersect the earth. The relative positions, in Figure 11, of the cusp projection, the thick portion of the plasma sheet, and the boundary layer samples suggest that processes in the boundary layer (e.g., merging of boundary layer field lines along the flanks of the tail) may serve to populate the plasma sheet with the relatively hot plasma that is one of its identifying features.

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Ground magnetograms used in this article were obtained from WDC-A for geomagnetism.

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Figure Captions

Figure 1. H- or X- component magnetograms from several stations on July 2, 1968. The magnetic latitude (λ_m) of each station is given and the approximate magnetic local time (MLT) at 0000 UT and at 0400 UT is indicated at the ends of each trace.

Figure 2. Data from Vela 4A on July 2, 1968. At the top the average number of counts per energy channel of the electrostatic analyzer, recorded in each proton spectrum, is plotted. The black triangles along the line above the data points mark the times when the analyzer aperture crossed the subsolar meridian of the satellite. Flow velocity vectors derived from the spin modulations of the proton data points are drawn emanating from the second line. The sunward direction is toward the top of the diagram, as illustrated by the small vector in the box indicating sunward flow at 100 km/sec. The next two graphs show the density and temperature of "plasma" electrons ($63 \text{ eV} < E_e < 18.5 \text{ keV}$) measured with the electrostatic analyzer. The count rate of a solid state detector sensitive to electrons ($E_e \gtrsim 30 \text{ keV}$) is plotted at the bottom. Multiply by 20 to obtain absolute flux (electrons/cm²-sec-ster). The solar magnetospheric latitude and longitude (λ_{SM} and ϕ_{SM}) are shown at the bottom. dZ_{SM} is the estimated distance of the satellite from the neutral sheet.

Figure 3. H- or X- component magnetograms from several stations. M marks the approximate time of magnetic local midnight.

Figure 4. Data from Vela 4A on March 5, 1968. Details are the same as in the caption of Figure 2 except here the count rate of a solid state detector of electrons ($450 \text{ keV} < E_e < 2.25 \text{ MeV}$) has been added. Multiply this count rate by 20 to obtain absolute flux (electrons/cm²-sec-ster).

Figure 5. A mercator map of the anti-earthward portion of the $\sim 18 R_E$ spherical surface on which the Vela satellites orbit. The coordinates are solar magnetospheric latitude and longitude. The map is divided into 10° by 10° sectors. The line radiating from the center of each sector represents the apparent magnitude and direction of plasma flow that would be derived from the Vela 4B analyzer's response to an actual bulk flow of protons toward the sun (i.e., parallel to the solar magnetospheric X axis) at 100 km/sec. The length of the arrow above the diagram represents 100 km/sec.

Figure 6. Map, as in Figure 5, showing the flow vectors derived by averaging all flow measurements made by Vela 4B in each 10° by 10° range of solar magnetospheric latitude and longitude. Multiply the number in each box by 9 to determine the total number of satellite rotations from which the data were obtained to derive the corresponding flow vector.

Figure 7. Map, as in Figures 5 and 6. The flow vectors shown here were derived from single rotations of Vela 4B for which the spin

modulation of the proton flux was very clear (see text).

Figure 8. Data from Vela 4B on August 10, 1967. At the top the average number of counts per energy channel of the electrostatic analyzer, recorded in each proton spectrum, is plotted. The black triangles along the line above the data points mark the times when the analyzer aperture crossed the subsolar meridian of the satellite. Flow velocity vectors derived from the spin modulations of the proton data points are drawn emanating from the line below the proton data. The small inserted box contains two arrows. One, labeled $V_{\perp} = 100$, designates the vector that would be derived from a proton flow at 100 km/sec perpendicular to the satellite's spin axis. The other arrow, labeled $V_s = 100$, shows the vector that would be derived from a proton flow at 100 km/sec toward the sun. Many of the derived vectors point in a direction nearly opposite to that of the latter vector, indicating a proton flow approximately in the anti-sunward direction. The response of a solid state detector of electrons, $E_e \gtrsim 36$ keV is shown at the bottom. Multiply the count rate by 20 to obtain electrons/cm²-sec-ster. The satellite's position is shown at the top of the figure.

Figure 9. Map showing segments of Vela orbits through the magnetotail along which were detected proton fluxes characteristic of the boundary layer (the thin lines). (The heavy lines in the figure are not relevant to the present discussion.) The

coordinates are solar magnetospheric longitude (ϕ_{SM}) and distance from the neutral sheet (dZ_{SM})

Figure 10. Suggested variations of plasma sheet dimensions and of plasma flow during a substorm. The plasma sheet is the hatched portion of each diagram. Arrows indicate the direction and magnitude of plasma flow. The hypothetical position of a Vela satellite is shown by the dot labeled V. The times (T) refer to substorm time, with $T = 0$ being the time of "breakup" or beginning of the expansive phase of the substorm. The interplanetary field direction is shown by $\overline{B}_I$ and the dashed curves indicate flow of magnetic field lines. The star in (b), (c) and (d) suggests the site of magnetic reconnection in the tail.

Figure 11. A map of the "Vela sphere" at $r = 18.5 R_E$. The dots indicate intersections of magnetic field lines from the polar regions with the sphere. The field lines are identified by the latitude (λ_m) and the magnetic local time of their polar cap intersections. (The model used in this projection is briefly described in the text.) The hatched area contains dayside cusp field lines projected to the Vela sphere. See text for further discussion of details.

VELA 4A JULY 2, 1968
 $r \approx 18.2 R_E$

RELATIVE
COUNTS

SUNWARD
100 km/sec

DENSITY
(cm^{-3})

ELECTRONS ($63 \text{ eV} < E_e < 18.5 \text{ keV}$)

TEMP ($^{\circ}\text{K}$)

ELECTRONS ($E_e > 30 \text{ keV}$)

RELATIVE
COUNT RATE

UT 0125 0130 0135 0140 0145 0150 0155 0200 0205 0210

λ_{SM} 0
 ϕ_{SM} 240
 dZ_{SM} -0.2

-1
241
-0.3

Figure 2

Figure 3

VELA 4A MARCH 5, 1968
 $r \approx 18.6 R_E$

Figure 4

Figure 5

$V_L = 100 \text{ km/sec}$

$K_p > 1+$

Figure 6

Figure 7

Figure 8

PLASMA SHEET (70eV - 1.5keV)

— STREAMING
 — STATIONARY

Figure 9

Figure 10

Figure 11