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DAVID P. STERN

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Unipolar Induction in the Magnetosphere

David P. Stern
Theoretical Studies Branch
Goddard Space Flight Center
Greenbelt, Maryland 20771

Abstract

A new theory is described for the production of electric currents in the magnetosphere and for the transfer of energy from the solar wind to the magnetosphere. Assuming that the magnetosheath has ohmic-type conduction properties, it is shown that unipolar induction can energize several current flows, explaining (among other things) the correlation of the east-west component of the interplanetary magnetic field with polar electric fields and with polar magnetic variations. In the tail region unipolar induction can account for effects correlated with the north-south component of the interplanetary magnetic field. In particular, if that field points southwards, a large energy input into the magnetosphere is possible.

UNIPOLAR INDUCTION

By Helmholtz's theorem any electric field $\underline{E}$ can be resolved into an irrotational part $(- \nabla \phi)$ and a solenoidal divergence-free part. Maxwell's equations then show that the irrotational part is caused by distributed charges, while the solenoidal component is induced by time dependence of the magnetic field $\underline{B}$.

In a medium at rest, only the solenoidal part of the field can induce steady electric currents in ohmic conductors, or change the total energy of particles. If, however, some parts of the medium are moving relative to other parts, steady currents can still be created even when $\partial \underline{B}/\partial t$ vanishes, provided they flow in current loops that partially pass through the moving medium. This phenomenon is termed unipolar (or homopolar) induction.

Unipolar induction occurs because in a moving medium the electric field which causes the flow of current is not the field $\underline{E}$ derived in some standard frame of reference F_0 but the local field $\underline{E}^*$ in the frame F^* of the medium. If F^* moves with a velocity $\underline{v}$ relative to F_0, one gets to the lowest (non-relativistic) order

$$\underline{E}^* = \underline{E} + (\underline{v} \times \underline{B}) \qquad (1)$$

If $\partial \underline{B}/\partial t$ vanishes, $\underline{E}$ is irrotational and around any closed contour s

$$\oint_s \underline{E} \cdot \underline{ds} = 0 \qquad (2)$$

The effective e.m.f. driving a current around s will then be

$$\oint_s \underline{E}^* \cdot \underline{ds} = \oint_s (\underline{v} \times \underline{B}) \cdot \underline{ds} \qquad (3)$$

and this may well be non-zero. If the electrical conductivity of the medium permits it, a steady unipolar current will then tend to flow around s . Note that although $\mathcal{E}$ alone is not sufficient for a quantitative derivation of the pattern of current flow, it can be calculated without knowledge of $\underline{E}$, the electric field due to distributed charges: this property is useful in magnetospheric applications.

Historically unipolar induction represents the earliest method for the electrodynamic generation of steady currents, having been discovered by Michael Faraday in 1831 [Faraday, 1952] . In Faraday's disk dynamo (Fig. 1) a metal disk rotated around an axis parallel to a magnetic field and the circuit was completed by a non-rotating conductor touching the disk near its rim and near its middle. Viewed from the non-rotating frame, ($\underline{v} \times \underline{B}$) is radial on the disk and vanishes elsewhere in the circuit, so that $\mathcal{E} \neq 0$. It can easily be shown that the force density $\underline{j} \times \underline{B}$ due to the unipolar current in this case opposes the motion, so that if a steady rotation of the disk is required energy must be continuously supplied to it. This energy is ultimately converted to heat by the ohmic dissipation of the unipolar current.

UNIPOLAR INDUCTION IN THE MAGNETOSPHERE

Since the solar wind flows rapidly along the boundary of the magnetosphere, $\mathcal{E}$ will in general not vanish for closed circuits which connect it with the magnetospheric interior. Thus, in principle, unipolar currents may exist and feed energy from the solar wind into the magnetosphere. It may be mentioned in passing that the earth's rotation may also lead to unipolar induction and that this has been investigated in the past [e.g. Backus, 1956 ; Terletsky, 1960] . We will, however, omit this factor here since the velocities involved and the expected magnitude of the effect are rather smaller than those obtained with the solar wind.

Qualitatively it will be shown that at least two types of unipolar current may exist, caused by two different components of the interplanetary magnetic field. A quantitative treatment would be very difficult, due to the non-ohmic character of electric conduction in most of the medium. Instead of going into details of this conduction we will only classify the ability of various parts of the magnetosphere to carry electric current, in decreasing order, as follows:

(1) Along magnetic field lines conductivity is very high, limited mainly by the number of particles available and by their velocity.

(2) Across a magnetic "null sheet" or along a magnetic "neutral line" particles can move in the "meandering mode" [Sonnerup, 1971] which carries them across the field at an appreciable fraction of their total velocity. We may then expect current densities of the

same order as those possible along field lines, but only in a region of relatively small cross-section.

(3) The ionosphere is a fairly good ohmic conductor but with anisotropic conductivity. One may write there

$$\underline{j} = \sigma_0 \underline{E} + \sigma_1 \underline{E} + \sigma_2 (\underline{B} \times \underline{E}) \tag{4}$$

where σ_0, σ_1 and σ_2 are called the parallel, Pedersen and Hall conductivities. In the regions relevant to the present theory σ_0 is relatively large, σ_2 is of the order of up to $3 \cdot 10^{-4}$ mho/meter and σ_1 is smaller still by a factor 3 - 5, everything depending strongly on altitude and also on solar illumination and on auroral precipitation, if present [Swift, 1972; Maeda and Kato, 1966 and references cited there]. Note that the Pedersen current is dissipative ($\underline{E} \cdot \underline{j} > 0$) but the Hall current is not. In fact, if one replaces the conductivities by their averages (i.e. treats the ionosphere as an averaged 2-dimensional sheet) the Hall current will be very nearly divergence-free, since both $\underline{E}$ and $\underline{B}$ are almost totally irrotational: thus the Hall current will naturally circulate, without any of the considerations required from unipolar induction. We therefore will assume, in conduction orthogonal to $\underline{B}$ in the ionosphere, that the Pedersen current is the one that completes the unipolar conduction path and that the Hall current is merely a by-product of the associated electric field — even though the latter may well exceed the former and produce larger magnetic effects.

(4) Currents can be carried across field lines by guiding center drifts. Taking a sample of the particle population having drift velocity $\underline{v}_d$, density N and charge q , one finds [e.g. Longmire, 1963]

$$\underline{j} = q N \underline{v}_d + \nabla \times \underline{M} \qquad (5)$$

where $\underline{M}$ is the magnetic moment density, oriented along $(-\underline{B})$. If a particle population is given in which the energy, charge and drift velocity vary, the total current carried by it may be obtained by superposing contributions of the above form.

(5) We will assume that the current carried across magnetospheric field lines by mechanisms other than the above is negligible, with the possible exception of currents in the tail's plasma sheet.

One may furthermore distinguish between "coasting" and "lossy" currents. Currents of the first type experience no dissipation and continue almost indefinitely without any e.m.f. driving them: the ring current due to drifting trapped particles near the earth is a good example of this. A "lossy" current, on the other hand, experiences an energy loss which cannot be recovered by it, through collisions or in other ways: ohmic conduction in the ionosphere (eq. 4) typifies this kind. A lossy current will not flow without an e.m.f. driving it, while in a "coasting" current an e.m.f. leads to particle acceleration — if indeed $\underline{E}$ does not then disrupt the current flow through $(\underline{E} \times \underline{B})$ drifts.

The preceding points are mainly relevant to currents inside the magnetosphere. For a unipolar current to flow, conduction outside the magnetosphere is also necessary. Surrounding the magnetosphere is a flow of solar wind plasma which has been somewhat heated and disoriented by passage through the earth's bow shock. This flow is called the magnetosheath and it has the following properties:

(1) It flows with a velocity which is about 70% of that of the undisturbed solar wind, and it is deflected by the front of the magnetosphere acting as an obstacle [Argo et al., 1967].

(2) Unlike the solar wind, it contains energetic electrons due to bow-shock heating [Montgomery, 1970].

(3) Its magnetic field somewhat resembles the interplanetary magnetic field from which it originated; some of the changes are [Behannon and Fairfield, 1969]: an amplification by a factor of up to 4 near the front magnetopause, due to compression of the convecting plasma, a tendency for field lines to become "draped" along the flanks of the tail and a general "disorientation" of the field there, due to fluctuations and irregularities. Nevertheless, even next to the tail, the field components orthogonal to the earth-sun line maintain a preference for the same orientations as those existing in the adjoining solar wind at the same time.

(4) It exhibits many fluctuations and irregularities [Fairfield and Ness, 1970].

We now assume that the magnetosheath conducts electric current, in any direction, approximately to the same extent as guiding center drifts are capable of doing inside the magnetosphere, i.e. at "level 4" of the list drawn up earlier. Unlike the ionosphere, the sheath has practically no collisions, so that cross-field conduction may require a different mechanism. Tidman and Krall [1971] and Sagdeev [1966] have derived "equivalent collision frequencies" in fluctuating plasmas, proportional to the energy density of the waves which characterize these fluctuations, and this may well be responsible for the sheath's conductivity.

While the magnitude of the anomalous conductivity due to this cause is hard to estimate, there exists indirect evidence that it is sufficiently high for the theory which follows to hold. Specifically, it will be seen in the next section that at least one of the current patterns attributable to unipolar induction appears to be controlled by ionospheric conductivity. While the conductivity of the other parts of that circuit — the magnetosphere and the ionosphere — may still be less than that of the ionosphere, the increased dimensions of these parts apparently more than make up for this difference and the true "bottleneck" of the flow remains in the ionosphere.

In calculations involving the interplanetary magnetic field $\underline{B}_i$, it can be conveniently resolved in so-called solar magnetospheric coordinates. In these coordinates the x-axis points at the sun, the y-axis is orthogonal to the plane containing $\hat{\underline{x}}$ and the earth's dipole axis (with $\hat{\underline{y}}$ pointing from dawn to dusk) and the z-axis lies in that plane and points approximately northward. The component B_{ix} is then parallel to the sheath flow (except in the region near the front magnetopause, which is neglected here) and thus produces no unipolar current. The other two components, however, do.

UNIPOLAR INDUCTION DUE TO B_{iy}

The interplanetary magnetic field is basically the solar field, dragged out by the solar wind and twisted (on the average) into a spiral pattern by solar rotation. Thus B_{iy} is generally positive for field lines leaving the sun and negative for those heading sunward . Observations indicate [Wilcox, 1968 and references listed there] that the sense of the interplanetary field (i.e. inward or outward) detected near the ecliptic plane is uniform over a small number of regions (typically 2 or 4), termed sectors . Thus the sign of B_{iy} is generally (though not exclusively: see Friis-Christensen et al. [1972b]) an indicator of sector polarity.

For the purposes of this work the geomagnetic field lines will be divided into three groups, depicted schematically in Figure 2 . Those that originate at low and medium (geomagnetic) latitudes return to earth and have a general dipole-like character. Those emanating from the polar caps are swept back into the tail: the exact mode in which they terminate is not known and bears no significance here. Finally, the narrow region between these two groups of field lines contains lines which lead to the boundary of the magnetosphere and to the plasma sheet (Figure 3) and will be called the transition region.

The front of the transition region is connected to the cusps (or "clefts" [Heikkila, 1971]), two slot-like regions which separate field lines which close near the earth from those swept into the tail. The rear leads into the plasma sheet, where field lines are grossly stretched: the minimum field intensity on such lines seems to be of the order of 2γ and they may contain "bubbles" with field reversals and neutral lines [Schindler and Ness, 1972]. The boundary between these two groups of field lines is not well known and has therefore been indicated by a zig-zag line in Figure 2. This boundary will contain field lines that form the flank of the tail region and are thus in contact with the sheath flow.

If $B_{iy} > 0$, the z-component of $\underline{v} \times \underline{B}_i$ points southwards, and if $B_{iy} < 0$ it points northwards. Two possible configurations then exist for unipolar currents induced by B_{iy}, as shown in Figure 4. One possibility occurs if the current enters by one cusp, passes to the other cusp by means of the global ionosphere, leaves through that cusp and completes the circuit via the magnetosheath. In the other mode, which is confined to a single hemisphere, the current enters via either of the cusps, flows in the ionosphere to the rear of the transition region, from there reaches the magnetosheath either directly through the flank lines or by a route which in part passes the plasma sheath, and then again completes the circuit by way of the magnetosheath. It will be noted that the second mode (which can occur simultaneously in both hemispheres) has only half the unipolar e.m.f. as the first one, but its ionospheric conduction path is much shorter. In either case the electric field patterns created near one pole would be the reverse of those produced near the other pole.

Two recent observations, independently made, tend to confirm the existence of such currents. On one hand, Heppner and his co-workers [Heppner, 1972a,b] used a double floating probe on OGO 6 to measure the dawn-dusk component of the polar electric field and obtained patterns which clearly correlated with B_{iy} (more precisely, they used the component $B_{i\varphi}$ tangential to the ecliptic and normal to the earth-sun line, which differs slightly) . The basic polar pattern of the electric field (due to a different source) is that of a constant dawn-to-dusk field, as shown in Figure 5-a , and this was found to undergo various modifications, of which (5-b) and (5-c) are typical. In general, patterns observed near one pole resembled those obtained by interchanging east and west in the patterns obtained at the opposite pole.

To understand the mechanism, consider the case of $B_{iy} > 0$, so that $\underline{v} \times \underline{B}_i$ in the sheath has a southward component: the unipolar current then flows out of the northern polar region. If the second of the patterns in Fig. 4 is then produced (as seems likely, for reasons which will be described later), the ionospheric Pedersen current will flow from the rear of the northern transition region into its day side.

Now it is important to note that this current flows mainly into the center of the cusp, where the e.m.f. (which is proportional to the distance from the equatorial plane at which the field line carrying the current enters the sheath flow) is highest. This means that the associated electric field will converge on the center of the frontside transition region, as shown in Figure 6 where this part has been shaded.

This will increase the dawn-to-dusk component of the electric field near the dawn side and decrease it on the dusk side, leading to a pattern similar to (5-c) which, indeed, correlates with positive B_{iy}. If $B_{iy} < 0$, everything reverses and the pattern resembles (5-b), which indeed was found by Heppner to be correlated with negative B_{iy}.

It may be added here that Heppner also found a correlation between pattern (5-a) and $B_{iy} > 0$, for which this theory can offer no explanation.

The second observation is the correlation between B_{iy} and the magnetic variation at very high magnetic latitudes, deduced by Svalgaard and his co-workers [Svalgaard, 1968, 1972 ; Friis-Christensen et al., 1972 a, b ; Jørgensen et al. 1972] and independently by Mansurov [Mansurov, 1969 ; Mansurov and Mansurova, 1969] . Basically, what Svalgaard found was that at very high latitude stations (Thule in the north, Vostok in the south) the mean vertical component of the geomagnetic field was generally higher than average for one sign of B_{iy} and smaller than average for the opposite sign. The effects in opposite polar regions were in opposite directions and seemed to be proportional to B_{iy}, with the factor of proportionality varying with the season [Wilhjelm and Friis-Christensen, 1972] ; in the northern polar cap, $B_{iy} > 0$ decreased the field below average, and this is indeed the expected effect of Hall currents like those shown by broken arrows in Figure 6 , for points inside their circulation.

Two features of this effect provide significant additional information. First, the amplitude of the effect had a marked seasonal variation, being of order 20 - 30 γ for each 1 γ in B_{iy} during the summer (for the afternoon magnetic field in Thule) but several times smaller in winter.

This seems to indicate that the first mode of current flow (in by one cusp and out by the other) is relatively unimportant, since otherwise the effects in both polar caps would be roughly equal. Furthermore, if the seasonal variation is due to increased ionospheric conductivity over a sunlit polar cap (as seems likely), this means that the unipolar current is controlled by ionospheric conductivity, the impedance of all other parts of the circuit (including the magnetosheath) having a relatively small effect.

Assuming the ionospheric conduction path to be 2000 km long, 2000 km wide and 100 km thick, and taking the average Pedersen conductivity to be $5 \cdot 10^{-5}$ mho meter^{-1}, we obtain a resistance of 0.2 ohm. If v is the sheath velocity and h is the difference in z between the ends of the external circuit, let

$$\begin{aligned} v &= 200 \text{ km/sec} \\ B_{iy} &= 1\,\gamma = 10^{-9} \text{ weber/ m}^2 \\ h &= 10\,R_e = 6 \cdot 10^7 \text{ meter} \end{aligned}$$

The value of B_{iy} was chosen as $1\,\gamma$ since we aim at deriving the proportionality constant mentioned earlier. The unipolar e.m.f. is then

$$\mathcal{E} = h\,v\,B_{iy} = 12{,}000 \text{ volt}$$

This gives a Pedersen current of about $6 \cdot 10^4$ amperes. If the associated Hall current is taken as 3 times larger and flowing in a circle of an average radius of 1000 km , one obtains a variation of about $100\,\gamma$

inside the flow loop, shown by broken arrows in Figure 6 . The fact that the actual effect is 3 - 5 times smaller than that may be attributed to "disorientation" of the magnetic field in the magnetosheath, relative to its value prior to passing the earth's bow shock.

The second feature is the observation [Friis-Christensen, 1972 a] that when B_{iy} reverses sign there seems to exist a delay of about half an hour to an hour between this reversal and that of the polar magnetic field pattern, and that apart from this delay, even brief reversals have a noticeable effect on the polar magnetic field [Wilhjelm and Friis-Christensen, 1972] . This may be viewed as an effect due to self-inductance. If we approximate the current pattern by a toroidal loop 10^6 km^2 in cross section (this is not critical) and with a major radius of 10 earth radii, we obtain an inductance of about 360 henry . Combined with the previously derived resistance of 0.2 ohms, this gives a time-constant of half an hour. If this explanation is correct, the observed delays should increase significantly in the wintertime.

UNIPOLAR INDUCTION DUE TO B_{iz}

The north-south component B_{iz} of the interplanetary magnetic field (which the sheath field follows, on the average) has received considerable attention ever since it was discovered [Fairfield and Cahill, 1966] that substorm activity correlates with negative (i.e. southward) B_{iz} . This was taken as evidence for Dungey's theory of field line merging [Dungey, 1961 ; Axford et al., 1965] which requires a southward field. However, as will be shown in what follows, a southward field also has another effect — it intensifies the cross-tail electric field and the associated energy input into the plasma sheet. This may well be an important factor in the creation of substorms.

The magnetic field in the tail [Behannon, 1970] is mainly characterized by a relatively large x-component, changing from about 10 γ north of the plasma sheet to -10γ south of it. In addition, there seems to exist a northward z-component averaging 2γ, varying not only in its magnitude but even in sign [Schindler and Ness, 1972]. The strength of this component is such that the "meandering" mode, if it occurs, is probably confined to narrow filamentary regions of field reversal.

Using the x-component to derive $\nabla \times \underline{B}$ and assuming an effective length of 20 earth radii for the plasma sheet, one finds that a current of about $2.5 \cdot 10^6$ amperes flows across the sheet from dawn to dusk. This current may be viewed as closing the circuit loops of the magnetospheric boundary currents around the tail, one of which is shown schematically by the arrows in Figure 7. It is not clear whether this flow is "lossy" or not, though the latter possibility is suggested by the regular dawn-to-dusk electric field observed across the polar cap, which can be viewed at least in part as indicating a cross-tail electric field mapped down along field lines. Such a cross-tail field could also account for the asymmetry in energetic plasma sheet electrons observed by Vela satellites [Hones, 1968].

Now, the boundary region of the tail is penetrated by the sheath flow which exerts the confining pressure. The exact extent of this penetration is not clear -- the boundary is far less definite in the tail than it is on the front side — but it seems likely that the sheath plasma confining the tail will continue carrying its embedded magnetic field, which reflects the interplanetary field in the manner described earlier.

If $B_{iz} < 0$, the east-west component of $\underline{v} \times \underline{B}_i$ points from dusk to dawn and a unipolar e.m.f. is induced in the plasma sheet-magnetosheath circuit along the usual current flow direction, i.e. the one shown by arrows in Figure 7 or its counterpart south of the sheet. A positive B_{iz} will have an opposite effect. Thus a southward B_{iz} <u>reinforces</u> the normal dawn-to-dusk electric field, while a northward B_{iz} <u>diminishes</u> it.

The fraction of the unipolar e.m.f. appearing as a voltage across the plasma sheet depends on the impedance of the plasma sheet and the magnetosheath, which is not easily estimated. However, indirect evidence related to the electric drift of particles seems to indicate that this voltage is <u>not</u> small.

A dawn-to-dusk electric field $\underline{E}$ (as might be produced by a southward B_{iz}) produces $\underline{E} \times \underline{B}$ drifts which tend to bring particles closer to the middle of the plasma sheet, while an opposite $\underline{E}$ drives them outwards. Effects of this sort have been observed: when B_{iz} turns southward, prior to a substorm, the plasma sheet becomes thinner, and <u>Aubry and McPherron</u> [<u>1971</u>] have also found that while negative B_{iz} narrows the plasma sheet, positive B_{iz} makes it thicker. If these are effects of electric drifts, then $\underline{E}$ should be of a significant magnitude.

In addition, the variation of E from this source could also explain the DP2 geomagnetic variation, observed both in the polar cap and at low latitudes [Nishida, 1968 a, b ; Nishida and Kokubun, 1971] . This variation is correlated with B_{iz} , but the correlation is slightly delayed: Nishida [1968 b] deduced that the delay can be explained if one assumes that B_{iz} starts affecting the earth's field only when the plasma convecting it has moved 21 earth radii behind the bow shock. This is indeed the distance at which the plasma sheet begins, approximately, so that the cause of the variation could well be the cross-tail electric field, mapped down into the ionosphere.

Assuming B_{iz} to equal about 1γ [Coleman and Rosenberg, 1971] , estimating the sheath velocity at 200 km/sec and taking the tail width to be 10^5 km , one obtains a unipolar e.m.f. of 20,000 volts (this might have to be divided by a "disorientation factor" which in the preceding section was found to be 3 to 5). The important thing to note is that a current of $2.5 \cdot 10^6$ amperes is already flowing in the circuit, so that the electric field assumed here will deposit in it energy at the rate of $5 \cdot 10^{10}$ watts. This is only a factor 2 below the rate at which substorms energize the aurora, according to Axford [1967] , who also estimated a similar energy input by substorms into the auroral electrojet. Much (perhaps most) of this energy is given to plasma sheet particles.

While the exact process has not been worked out in detail, it would avoid some of the difficulties inherent in the field line merging theory of Dungey. In the usual view of the field line merging process [Yeh and Axford, 1970 ; Stern, 1966 and references there ; Parker, 1963] which was originally developed to explain solar flares, two streams of oppositely magnetized plasma collide and emerge at right angles to their original motion, stripped of their magnetic energy but with extra energy (in various forms) making up for this loss. When this is applied to the magnetospheric tail the flow into the neutral line is assumed to come from above and below the plasma sheet, yet observations indicate that such regions are practically empty of plasma [Vasyliunas, 1970].

The present theory shows that an energy input will exist even in the absence of field line merging. While neutral lines could still exist in the form suggested by Schindler and Ness [1972], it is possible that their role is more that of "accelerator tubes" for accelerating particles by means of the cross-tail electric field, rather than centers for merging flows.

CONCLUSIONS

It appears from the preceding considerations that unipolar induction between the magnetosphere and the moving magnetosheath is not only possible but indeed agrees with observations. Furthermore, these observations seem to indicate — at least in the first of the two examples discussed — that the ohmic-type conductivity assumed for the sheath is in fact high enough to cause the main limitations of the flow to arise in other parts of the circuit.

The unipolar process appears to be capable of accounting for magnetospheric phenomena which are correlated with the interplanetary magnetic field. In particular, it explains the recently discovered correlations shown by polar electric fields [Heppner, 1972 b] and by polar magnetic variations [Svalgaard, 1972] with the east-west component of the interplanetary magnetic field. Unipolar currents may also be produced by the sheath flow alongside the tail region; a southward component in the interplanetary magnetic field then leads to an intensification of the cross-tail electric field and this could be significant in the production of substorms.

Further work is still needed, in particular on the theory of the cross-tail current and on its relation to substorms. Further observations on the existence of neutral lines in the tail (as deduced by Schindler and Ness, 1972) and on particle fluxes near them would also be helpful here, as would be detailed observations of both horizonthal components of the polar electric field from a satellite in a low polar orbit.

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FIGURE CAPTIONS

Fig. 1 : Faraday's disk dynamo.

Fig. 2 : Schematic view from above the north pole of the regions on earth to which various types of field lines are connected.

Fig. 3 : Side view of the field lines of Figure 2 (not to scale).

Fig. 4 : Two possible modes by which the unipolar current due to B_{iy} may flow (not to scale). In each case, the e.m.f. for currents flowing through the middle of the cusp is proportional to the distance indicated by the straight vertical line.

Fig. 5 : Some patterns of the dawn-to-dusk component of the electric field observed by Heppner [1972 b] above the northern polar cap. Distance is plotted along the x axis, electric field intensity along the y axis.

Fig. 6 : Schematic view of the contributions to the polar electric field (small solid arrows) and Hall current (broken arrows) which may be produced by $B_{iy} > 0$.

Fig. 7 : Schematic cross-section of the magnetospheric tail, looking down towards the sun, showing one loop of the cross-tail current flow and the direction of the electric drift due to $B_{iz} < 0$.

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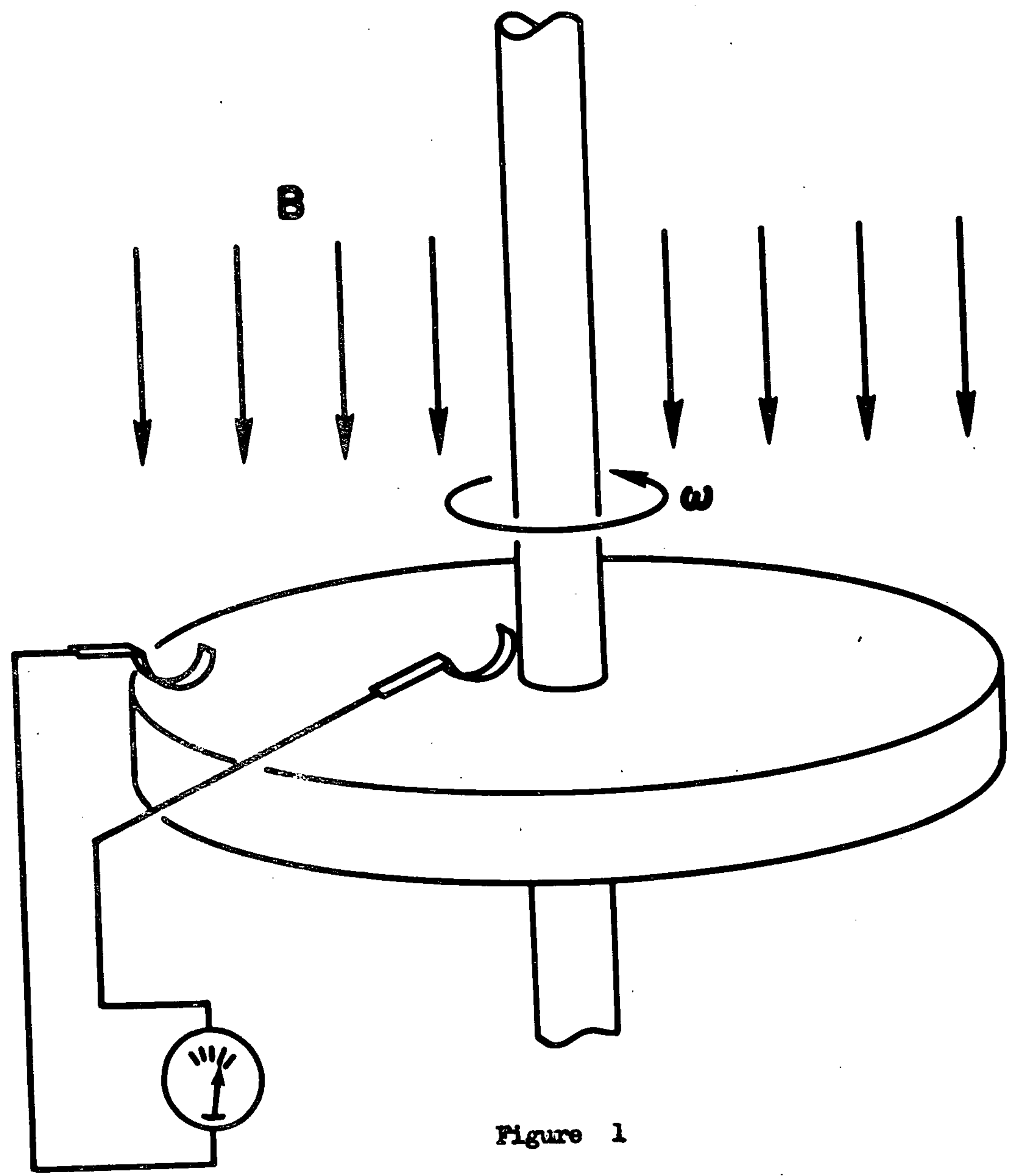

Figure 1

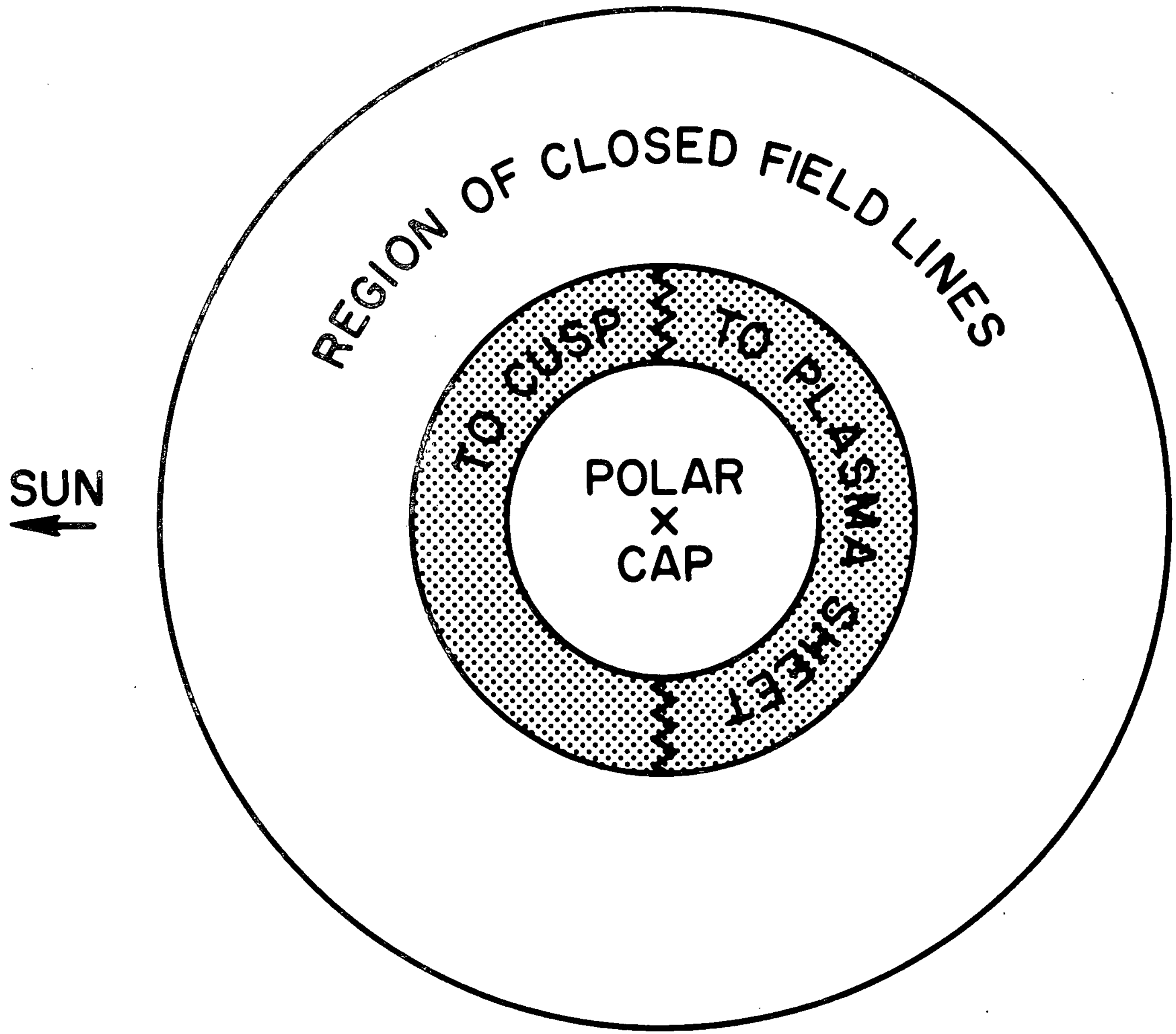
SUN
REGION OF CLOSED FIELD LINES
TO CUSP
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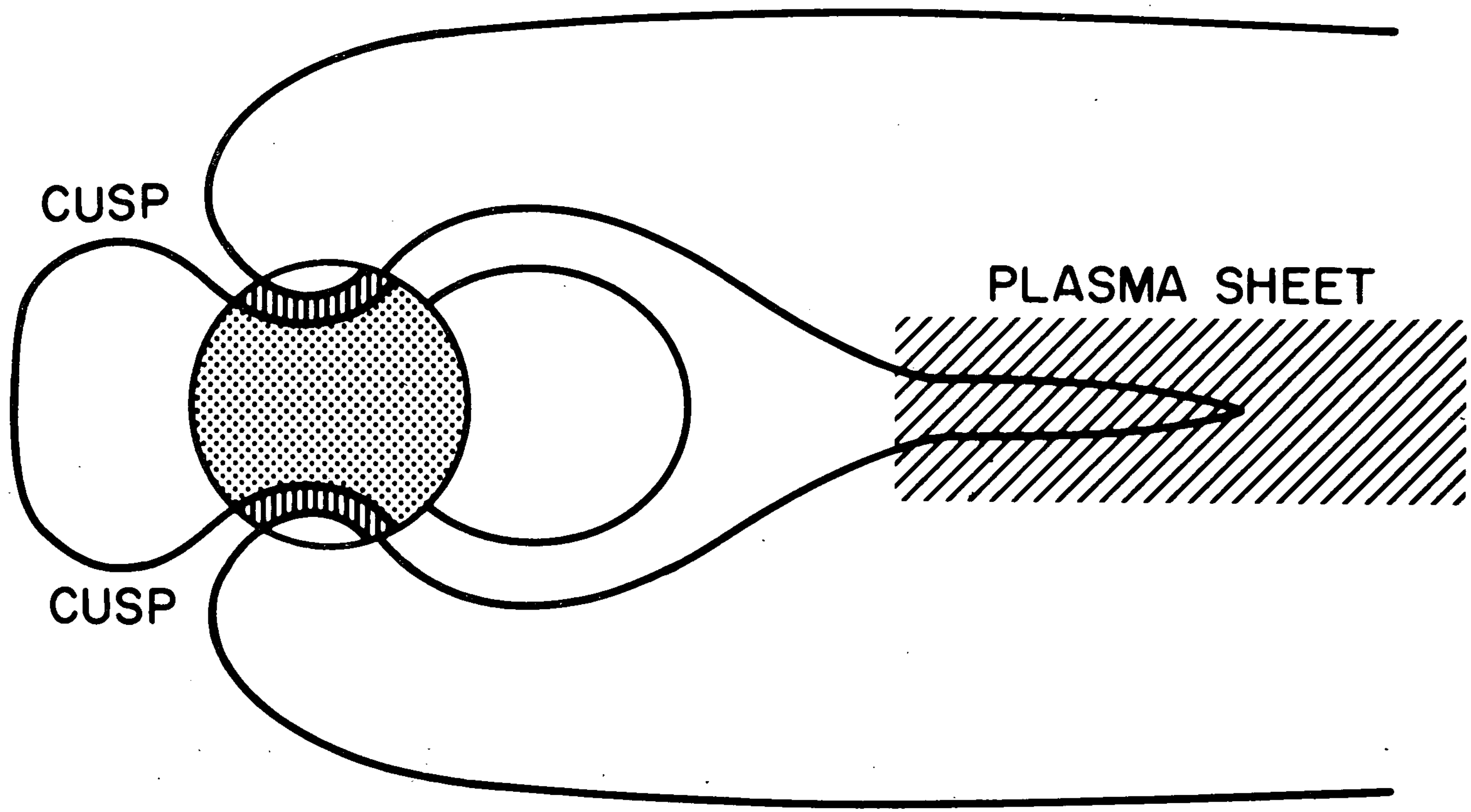
Figure 2



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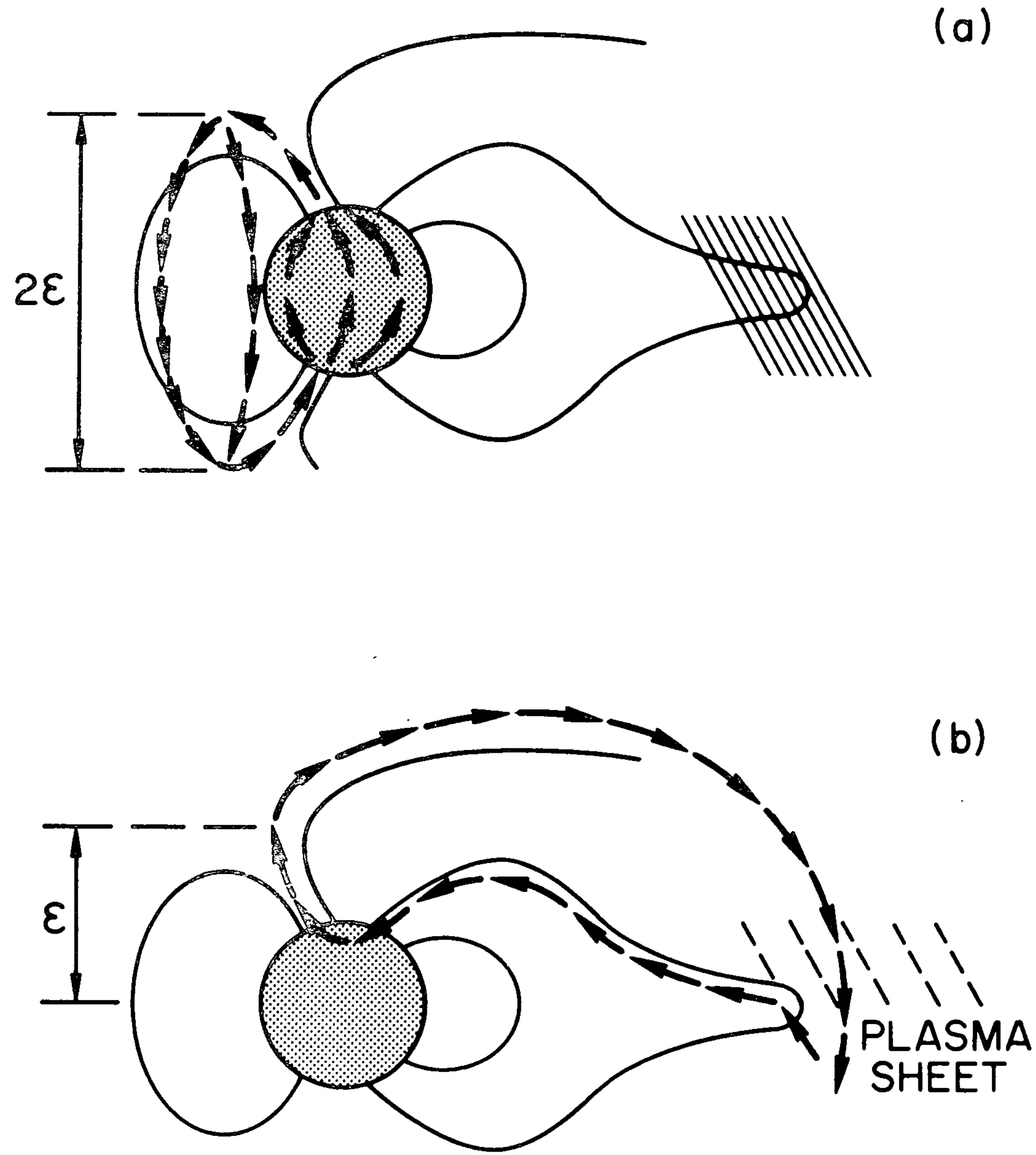

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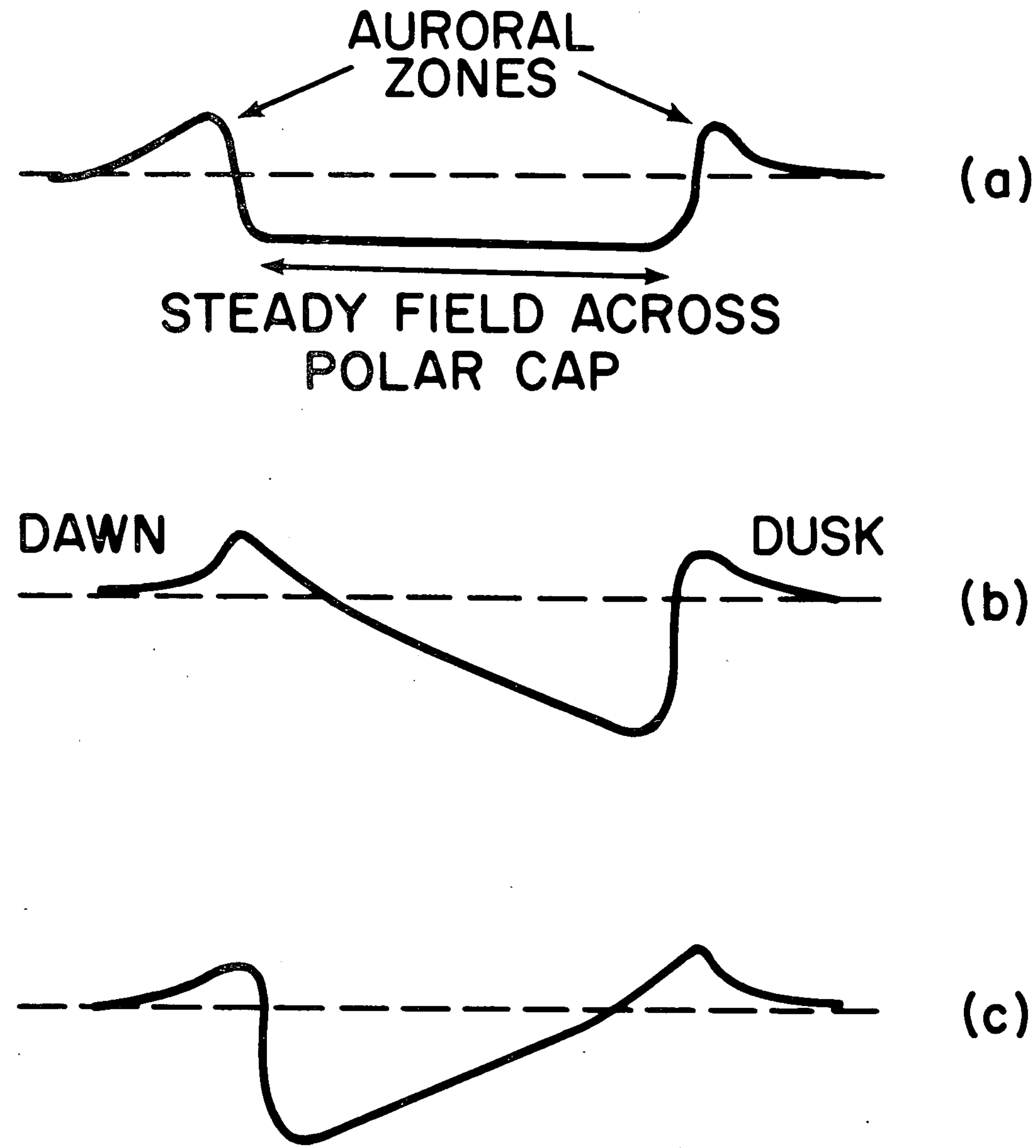

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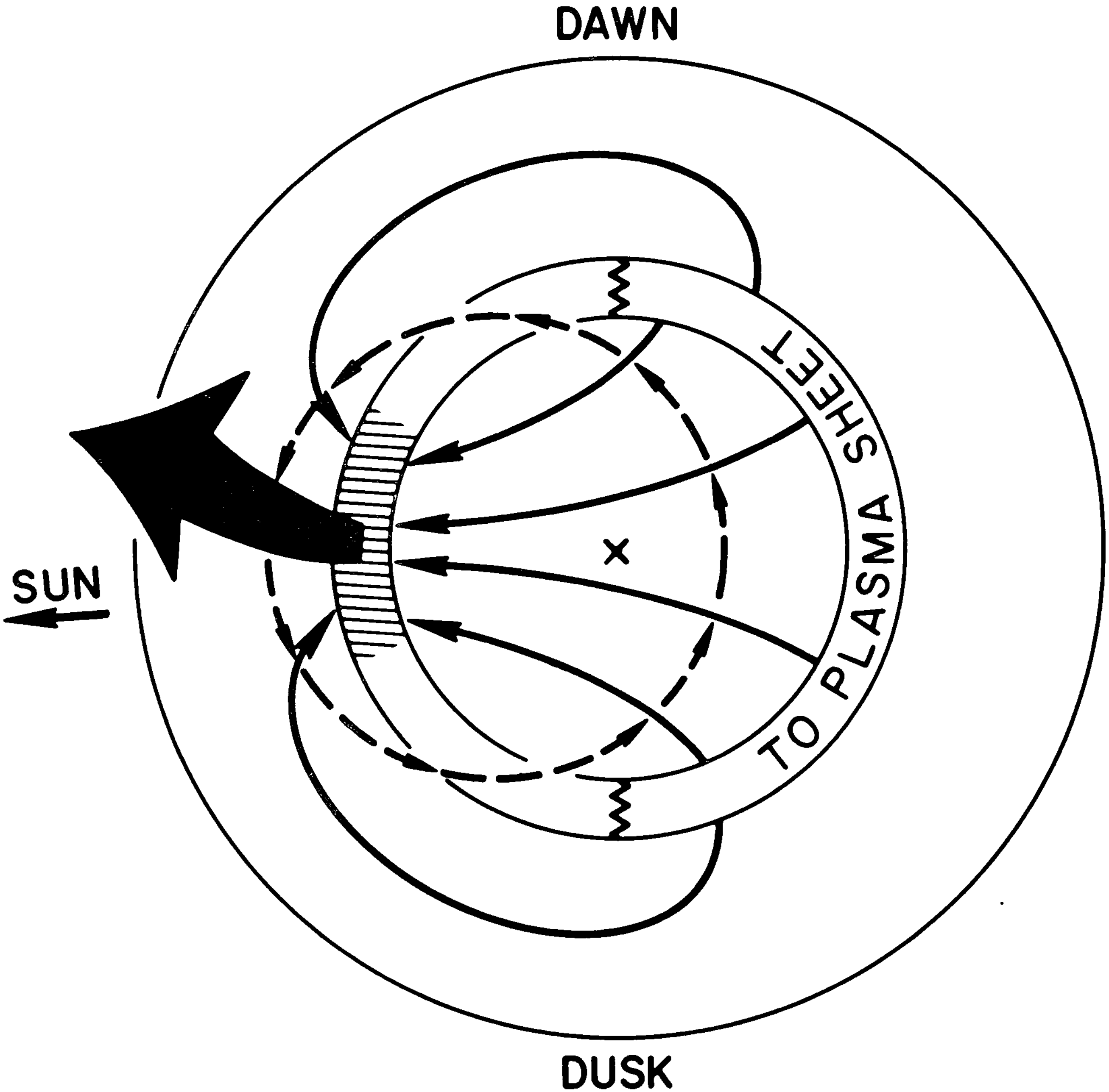

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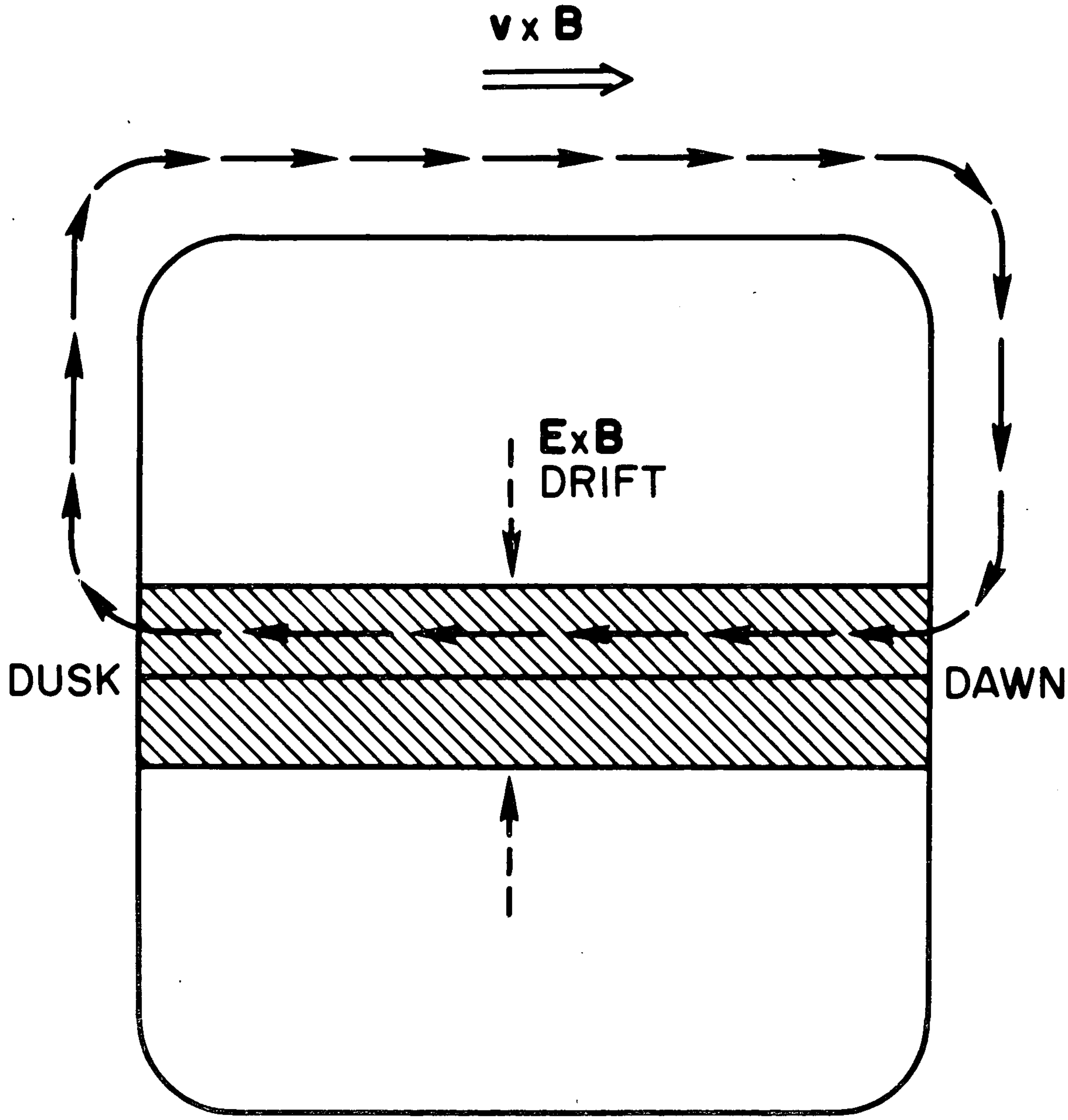

Figure 7