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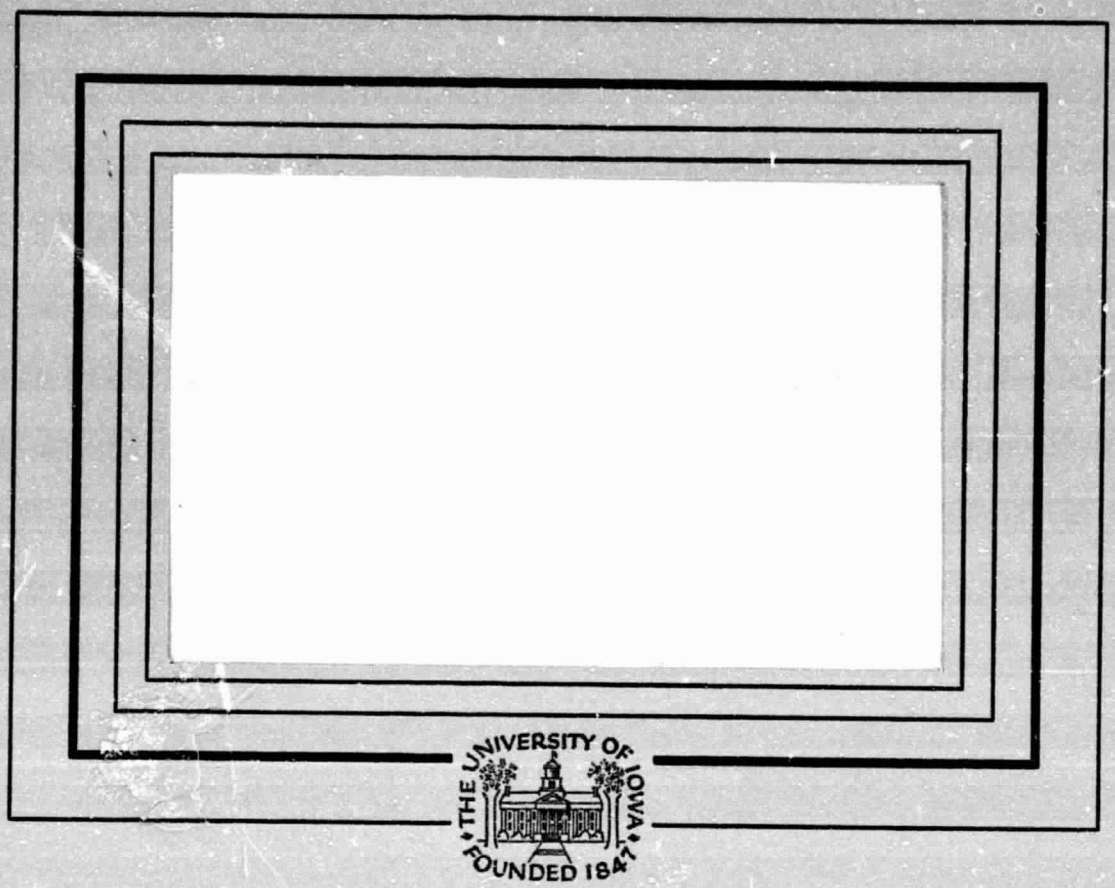

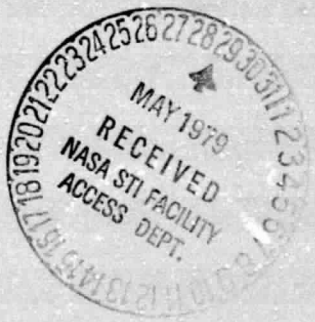

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Field-aligned Currents and Large Scale Magnetospheric Electric Fields

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ABSTRACT

A simplified model of polar cap large-scale electric fields [D'Angelo, 1977] is employed in order to visualize how large-scale field-aligned currents in the earth's magnetosphere are driven by their "generators". The region 1 and region 2 currents of Iijima and Potemra [1976a,b] and the cusp field-aligned currents of Wilhjelm et al. [1978] and McDiarmid et al. [1978] are apparently driven by different generators, although in both cases the solar wind is their ultimate source.

I. INTRODUCTION

In 1908 Kristian Birkeland argued that large-scale ionospheric currents are associated with the aurora, and suggested that these currents have their origin far from the earth, flowing along the geomagnetic field lines into or away from the high-latitude ionosphere.

The existence of field-aligned currents at northern and southern high latitudes has been confirmed by a number of observations, most clearly by experiments on the TRIAD and ISIS 2 satellites. This subject has been reviewed recently by Potemra [1978] and Potemra et al. [1979]. The large-scale pattern of field-aligned current [FAC] comprises the region 1 and region 2 current system of Iijima and Potemra [1976a, 1976b] as well as field-aligned currents observed in the dayside cusp. Region 1 and region 2 FAC's show a dependence on the y and z components B_y and B_z of the solar wind magnetic field, which is quite distinct from that of the polar cusp currents. It has been argued that region 1 and region 2 FAC's are driven by a "generator" distinct from that which drives the polar cusp currents [e.g., Iijima et al., 1978], although ultimately all high-latitude FAC flow must have its source in the solar wind.

It is the purpose of this paper to relate the high-latitude field-aligned current system to what we presently know about the

large-scale pattern of high-latitude ionospheric electric fields and their relation to solar wind parameters. Recently, a simplified model has been presented of polar cap electric fields [D'Angelo, 1977]. This model is of considerable help in visualizing also the large-scale features of FAC systems.

In Section 2 a summary of the FAC observations is given. In Section 3 the simplified model of polar cap electric fields [D'Angelo, 1977] is rediscussed. It is then used in Section 4 in order to visualize how the field-aligned currents are driven by their "generators". Section 5 adds a few comments and Section 6 presents the conclusions.

II. OBSERVATIONS OF FIELD-ALIGNED CURRENTS

A summary of the distribution and flow directions of large-scale field-aligned currents in the northern hemisphere is presented in Fig. 1 [from Iijima and Potemra, 1976b]. The region 1 currents flow into the ionosphere in the morning sector and away from the ionosphere in the evening sector. The region 2 currents, located equatorward of region 1, have a reversed flow direction at any local time. In the 2200 to 2400 MLT sector, the general area of the so-called Harang discontinuity, there appears an overlapping of the two-region flow patterns observed in adjacent local time sectors. This feature will not be discussed further in this paper. In the southern polar region the same basic flow pattern illustrated in Fig. 1 prevails, with the same field-aligned current flow at any given local time and invariant latitude location [Potemra et al., 1975].

In addition to the region 1 and region 2 currents, Birkeland currents have also been observed by a number of investigators in the ~ 1000 to ~ 1400 MLT sector, at invariant latitudes between ~ 75° and ~ 85°. These Birkeland currents are generally referred to as cusp field-aligned currents. Their flow pattern is less clear than for currents in region 1 and region 2. Some authors appear to have

emphasized certain aspects of the cusp currents, while others have concentrated on different features. A feeling for the situation can be gained by comparing the report of Iijima et al. [1978] with those of Wilhjelm et al. [1978] and McDiarmid et al. [1978].

In Iijima et al. [1978] the dominant cusp FAC features are a current flow away from the ionosphere in the pre-noon sector, a current flow into the ionosphere in the post-noon sector, and a zone of confused flow just around local noon. These three regions are labeled A, B, and C, respectively, in Fig. 1. In the southern cap the same situation prevails, flow in region A [pre-noon] being also away from the ionosphere and flow in region B into the ionosphere. The flow direction in A and B [as in region 1 and in region 2] is always the same--independent, in particular, of the y and z components, B_y and B_z, of the solar wind magnetic field. However, as is the case for region 1 and region 2, the current intensity depends on B_y and B_z.

Wilhjelm et al. [1978] emphasize a system of field-aligned currents in the cusp, around local noon, which consists of a pair of oppositely directed current sheets, oriented E-W along parallels of constant invariant latitude. The corresponding ionospheric currents are a Pedersen current connecting the sheets and an E-W or W-E Hall current between the sheets. A relation exists between the direction of the current flow in the sheets and B_y. When B_y is positive, the flow of the poleward field-aligned current is away from the iono-

sphere in the northern hemisphere. When B_y is negative, that flow is into the ionosphere. In the southern hemisphere, for any given B_y, the flow directions are reversed [e.g., Potemra, 1978]. The behavior of these field-aligned current sheets is consistent with that of the ionospheric current system, named DPY, which flows eastward in the northern hemisphere, for $B_y > 0$ [e.g., Friis-Christensen and Wilhjelm, 1975].

In spite of some apparent discrepancy between the reports of Iijima et al. [1978] and Wilhjelm et al. [1978], there is at least one possibility of combining the two sets of observations in one single comprehensive picture of the type which is schematically illustrated in Fig. 2 for the northern hemisphere. The A and B currents, as well as the region 1 and region 2 currents, have always the same direction, independent of B_y or B_z. In the immediate vicinity of local noon the current system consists of two currents sheets as in Wilhjelm et al. [1978], the poleward sheet to be identified with region C of Fig. 1. Thus, for $B_y > 0$ the region 1 current of the morning sector "extends" into the post-noon sector, while for $B_y < 0$ the region 1 current of the post-noon sector "extends" into the morning sector. This preserves the A, B, and C region features of Iijima et al. [1978] and a "zone of confusion [C]" arises when the region C observations are not organized on the basis of the sign of B_y. At the same time the double sheet structure

of Wilhjelm et al. [1978], with its dependence on B_y, is retained. Note that, for $B_y > 0$, the near-noon "throat" [Heelis et al., 1976] is displaced to the post-noon side with strong convection directed toward dawn; while, for $B_y < 0$ the "throat" is displaced to the pre-noon side and there is strong convection toward dusk. How the "extension" beyond noon of region 1 currents from the pre-noon or the post-noon sector may come about will be apparent in Section 4.

So far, we have discussed the spatial distribution and flow directions of large-scale field-aligned currents. We summarize next the information available on the intensity of these currents and its dependence on B_y and B_z.

The current density of field-aligned currents is generally in the range of $\sim 0.1\ \mu\ A/m^2$ to $\sim 3\ \mu\ A/m^2$. The total current for the entire region 1 - region 2 system is on the order of $\sim 10^6$ A.

The current density in, e.g., region 2, correlates quite well with the intensity of the auroral electrojets. Fig. 6 of Iijima and Potemra [1976a] shows a nearly linear relation between the Birkeland current density observed in region 2 in the pre-midnight to early morning sector and the simultaneous activity [ΔH] of the westward auroral electrojet. In turn, the intensity of the electrojet is known to correlate with the overall strength of high-latitude ionospheric electric fields, while a clear relationship between high-latitude ionospheric electric fields and the electric field in the solar wind has emerged from several types of observations [e.g.,

Mozer and Gonzalez, 1973; D'Angelo, et al., 1976]. Fig. 7 of Iijima and Potemra [1976a], similar to their Fig. 6, shows the relation between Birkeland currents into the ionosphere at the 1800-2300 MLT region 2 sector and the simultaneous intensity of the eastward electrojet.

Although the flow directions of the region 1 and 2 Birkeland currents do not change with different polarities of B_y, their relative dawn-dusk intensities are related to B_y. Positive B_y corresponds to larger Birkeland currents on the dawn side of the northern cap and on the dusk side of the southern cap. Negative B_y implies a reversal of these current distributions. This is precisely the behavior exhibited by large-scale ionospheric electric fields as measured, e.g. by Heppner [1972], Mozer et al. [1974], Mohl Madsen et al. [1976].

As far as the near noon, cusp FAC's are concerned, Wilhjelm et al. [1978] have noted a linear relation between the DPY current and the cusp field-aligned current related to B_y [their Fig. 9]. McDiarmid et al. [1978] find that the magnitude of the magnetic perturbation produced by a pair of oppositely directed field-aligned current sheets in the cusp is a linear function of $|B_y|$, both for positive and negative B_y. The correlation coefficient is 0.75.

III. A SIMPLIFIED MODEL OF POLAR CAP ELECTRIC FIELDS

Among the features of polar cap electric fields that a model must explain are:

a. polar cap convection most of the time, although not always, is in a general anti-sunward direction. Thus, electric fields in the cap are predominantly directed from dawn to dusk. This is in contrast with the convection at lower latitudes which is sunward. As a consequence, a two-cell convection pattern appears at high latitudes, of the type indicated, for instance, in Figure 8 of Heppner [1972]. [See also Mozer et al., 1974 and Mohl Madsen, et al., 1976].

b. convection velocities in the polar cap range from nearly zero to as much as ~ 2 km/sec or more, which corresponds to a range of intensities of polar cap ionospheric electric fields from nearly zero to as much as 100 mV/m or more. The average value of E is ~ 20-30 mV/m. The largest E's tend to occur when the north-south component of the interplanetary magnetic field B_z is large and negative.

c. the electric field strength, in the northern polar cap, is large on the dawn side and small on the dusk side, when the y-component of the interplanetary magnetic field B_y is positive, i.e.,

when the earth is in an "away" sector. In the southern polar cap the opposite is true. With $B_y < 0$ ["toward" sectors] the situation is reversed.

Several models of polar cap electric fields have been developed in the last several years. In particular, Gonzalez and Mozer [1974] have presented a model which is successful in accounting for almost all of the field properties listed under a. through c. However, their model is apparently unable to explain the fact that at times polar cap convection is directed sunward, rather than anti-sunward. This additional property of the cap fields, as well as all the other properties listed under a. through c., is accounted for in a simplified model of polar cap electric fields developed by D'Angelo [1977]. Only the main features of this model will be summarized here. For a more detailed discussion the reader is referred to D'Angelo [1977].

In D'Angelo's model the solar wind electric field may be transferred to regions well within the magnetosphere only if this transfer, or mapping, gives rise to a polar cap field directed approximately dawn-to-dusk. Where the mapping, on the other hand, would produce a cap field directed dusk-to-dawn, the plasma velocity immediately inside the magnetopause would be sunward, thus implying a large velocity shear, since the magnetosheath flow is anti-sunward. It is assumed in the model that velocity shear instabilities near the magnetopause are effective in "disconnecting" these regions of the

magnetosphere from the solar wind. Thus, for any given orientation of the solar wind magnetic field, the polar cap magnetosphere is divided into two distinct regions: an "open" region where transfer [or mapping] of the solar wind electric field can take place, and a "closed" region in which such a transfer is either severely limited or does not occur at all. The situation is illustrated in Fig. 3, which represents a cross-section of the earth's magnetosphere with a dawn-dusk meridian plane, for an observer looking toward the sun. Lines with arrows represent the solar wind and magnetospheric magnetic field. The solar wind magnetic field, in this example, has positive B_y and negative B_z components. The "closed" magnetospheric regions, where a mapping of the solar wind electric field would produce a dusk-to-dawn polar cap electric field, are indicated by shaded areas. As the direction of the solar wind $\underline{B}$ field changes the size and/or location of "open" and "closed" regions vary. For instance, when $B_y = 0$ and $B_z < 0$, the entire northern and southern caps are "open" and the size of the "closed" regions shrinks to zero. With reference to Fig. 3 it may be noted that, since near the magnetopause the magnetospheric field lines are bent tailward, the Poynting vector $\underline{S} = \frac{c}{4\pi} \underline{E} \times \underline{B}$ is directed into the magnetosphere in "open" regions of the magnetosphere and away from it in "closed" regions. Since the $\underline{E} \times \underline{B}$ direction is also the plasma flow direction, a substantial plasma "boundary layer" or "mantle" is expected only in "open" regions. As noted in D'Angelo [1977], this model explains why:

IV. FIELD-ALIGNED CURRENTS IN RELATION TO LARGE-SCALE E FIELDS

In this section the model of large-scale magnetospheric electric fields discussed in Section 3 is utilized to visualize current flow in the magnetosphere and in the ionosphere and, in particular, the behavior of field-aligned currents summarized in Section 2.

It is convenient for illustration purposes to begin our discussion with the case in which the interplanetary magnetic field B points precisely southward, namely with the situation in which $B_y = 0$ and $B_z < 0$. This is illustrated in Fig. 4. The interplanetary electric field points, in this case, exactly dawn-to-dusk and can be mapped without being inhibited by, e.g., velocity shear instabilities near the magnetopause over the entire northern and southern caps. The solar wind "generator" is applied between P_1 [positive potential] and P_2 [negative potential], thus producing the region 1 field-aligned currents and the cross-cap Pedersen currents indicated in the figure. Anti-sunward convection across the caps produces a return plasma flow in the ionosphere at lower latitudes which is directed sunward. This flow and its associated electric fields and Pedersen currents extend over a limited range of latitude, as discussed, e.g., by Vasyliunas [1970]. Termination of the Pedersen currents at the equatorward side of the sub-auroral region and the

condition that in steady state conditions $\nabla \cdot \underline{J} = 0$, require a second system of field-aligned currents [region 2] at a lower latitude than region 1. The magnitude of the field-aligned current density, $J_{\parallel}$, can be estimated from

$$J_{\parallel} = -\Sigma_P \frac{\partial E}{\partial y} - E\left[\frac{\partial \Sigma_H}{\partial x} + \frac{\partial \Sigma_P}{\partial y}\right] \qquad (1)$$

where E is the electric field, Σ_H is the height integrated Hall conductivity and Σ_p is the height integrated Pedersen conductivity. In writing Eq. 1 we take the x axis of a local Cartesian frame to be directed from E to W, the y axis equatorward along a meridian, and the z axis upward. Also, E depends on y alone. The three terms in Eq. 1 generally have the same sign at subauroral latitudes near 06 LT, and the first one is dominant. With $\Sigma_p \approx 10$ mhos and $\frac{\partial E}{\partial y} \approx 10^{-7}$ V/m^2 [e.g., Mozer et al., 1974] one obtains $J_{\parallel} \approx 10^{-6}$ A/m^2, i.e., a current density comparable to those measured by Iijima and Potemra [1976a,b]. On the dawn side the region 2 currents are directed, in both hemispheres, toward the equatorial plane, while on the dusk side they are directed away from it. From the region indicated as Q_1, current flows, through the dayside magnetosphere, to the region marked as Q_2, thus completing the global circuit. The current from Q_1 to Q_2 may be envisaged as flowing at the inner edge of the plasma

sheet which, according to Potemra [1978] [see his Fig. 8], approximately coincides with the separation in the equatorial plane between region 1 and region 2 field-aligned currents. It can be estimated that the current carrying capacity of the inner edge of the plasma sheet is sufficient to sustain the $\sim 10^6$ A of the system of field-aligned currents reported by Iijima and Potemra [1976a,b]. To this end, consider the equation

$$\nabla p = \underline{J} \times \underline{B} \qquad (2)$$

expressing the balance of the plasma pressure gradient by the $\underline{J} \times \underline{B}$ force. At the inner edge of the plasma sheet ∇p is directed away from the earth, thus implying a $\underline{J}$ directed from W to E. The magnitude of the total current, I, assumed to flow over an area which extends for a distance $L \approx 5\ R_E$ on either side of the equatorial plane, is found from the values of $n \simeq 1\ cm^{-3}$, $T_e \simeq 800$ ev, $T_i \simeq 4$ KeV given, e.g., by Vasyliunas [1972] for the plasma sheet [see his Fig. 8]. The radial extent of the current-carrying region is on the order of the radial e-folding length, ℓ, of the plasma pressure [at the edge of the sheet]. Obviously, for an estimate of the total current, no precise knowledge is required of this e-folding length since $I = J \cdot \ell \cdot 2L \simeq \frac{2Lp}{B}$. One finds $I \simeq 10^6$ A .

The cusp field-aligned currents, which leave or enter the ionosphere in those regions labeled A and B in Fig. 1, can also be

understood as forming part of the same global system of region 1 and 2 currents. To this end we view the ionospheric region A as being "fed" by the adjacent morning sector region 1 and the ionospheric region B as "feeding" the adjacent afternoon sector region 1. Continuity from A to B is assured by field-aligned current flow from A to the equatorial region, flow from W to E near the outer boundary of the dayside equatorial magnetosphere, and finally, field-aligned flow up the geomagnetic field lines into region B of the ionosphere. This is, of course, the same flow pattern for regions A and B envisaged by Iijima and Potemra [1976b] [see their Fig. 8].

If we now turn to the more general case of an interplanetary magnetic field possessing y and z components which are both non-vanishing, we obtain [instead of Fig. 4] the situation illustrated in Fig. 5. This figure refers to a case in which $B_y > 0$ and $B_z < 0$. It is easy to convince oneself that most of the current system remains the same as in Fig. 4. The main difference is in the appearance at this point of the "closed" regions [shaded areas] with their associated currents. A precise prediction of the current distribution within the "closed" areas is difficult since it must depend on the degree to which their dusk-to-dawn $\underline{E}$ field is inhibited by velocity shear turbulence near the magnetopause. The general character of the current system is very likely, however, of the type indicated in Fig. 5. One may expect in "closed" areas, an irregular or filamentary distribution of field-aligned currents, which would

correspond to locally larger or smaller levels ["patchiness"] of turbulence near the magnetopause. The polar cap "irregular" field-aligned currents discussed by Potemra et al. [1979] [see their Section 4.2] may correspond to our "closed" areas. With reference to Fig. 5, note that the solar wind "generator" is now applied to the magnetosphere between R_1 [positive] and R_2 [negative]. With $B_y > 0$ and $B_z < 0$, the most "active" portions of the polar caps are on the dawn side in the northern hemisphere and on the dusk side in the southern hemisphere.

Our discussion so far accounts for the global current system with the exception of the field-aligned currents in the near-noon cusp, i.e., the field-aligned current sheets reported by Wilhjelm et al. [1978] and McDiarmid et al. [1978]. Thus, we now turn our attention to them. Consider a cross-section of the earth's magnetosphere with a noon-midnight plane as shown in Fig. 6. The near noon current system will be driven by the voltage difference between regions such as S_1 and S_2. This voltage difference is proportional to the solar wind electric field component E_z, which, in turn, is proportional to B_y. For $B_y > 0$ the current flow is as indicated in Fig. 6; for $B_y < 0$ it is reversed. Evidently, this near noon current system has all the features needed to account for the observations of Wilhjelm et al. [1978] and McDiarmid et al. [1978]. Essentially this same picture for the cusp field-aligned currents is proposed by Barbosa [1979].

Thus, in agreement with Iijima et al. [1978], we may visualize the global system of field-aligned currents as being driven by two different "generators", which are now identified as a "main" generator responsible for region 1 and 2 FAC's, and a near-noon generator responsible for the cusp field-aligned current sheets of Wilhjelm et al. [1978] and McDiarmid et al. [1978]. In both cases, of course, high-latitude field-aligned current flow has its ultimate source in the solar wind.

V. COMMENTS

In this Section a few comments are presented which may help clarify the overall picture of polar cap electric fields and global systems of field-aligned currents of Sections 2 through 4:

a. For "average" solar wind conditions, B ~ 10 γ and V ~ 400 km/sec, the solar wind electromagnetic power flux onto the magnetosphere is 2 - 3 x 10^{11} watt [e.g., D'Angelo and Goertz, 1979]. A large fraction of this generally penetrates inside the magnetosphere, the extent to which penetration occurs being determined [see Section 3 or D'Angelo and Goertz, 1979] by the orientation of the interplanetary magnetic field, $\underline{B}$. As an order of magnitude, the power flux available to the magnetosphere is thus ~ 10^{11} watts. It is easily seen that this figure is very close to the power dissipated in the high-latitude ionosphere by Pedersen currents. The difference $I_1 - I_2$ between region 1 and region 2 field-aligned currents amounts generally to ~ 0.5 x 10^6 A [e.g., Potemra, 1978]. With a polar cap dawn-dusk voltage drop of ~ 7 x 10^4 volt, the power dissipated in one cap is ~ 3.5 x 10^{10} watt. Thus, for the northern and southern caps together, we obtain ~ 7 x 10^{10} watt. In the auroral and sub-auroral regions the Pedersen current dissipation is estimated, with an intensity of region 2 currents of ~ 0.5 x 10^6 A and a voltage drop

of $\sim 7 \times 10^4$ volt [the same as across the cap], to be $\sim 3.5 \times 10^{10}$ watts and for both hemispheres $\sim 7 \times 10^{10}$ watts. Altogether, we obtain for the entire high-latitude regions of the earth [caps, auroral and sub-auroral regions] $\sim 1.4 \times 10^{11}$ watt. Since the power deposited into the ionosphere by precipitation of auroral particles can be estimated to be smaller than the power dissipated by the Pedersen currents, we find that the solar wind electromagnetic power flux is sufficient to account for the total rate at which energy is deposited into the ionosphere and, in fact, is numerically about equal to it.

If we now consider the solar wind kinetic [particle] power flux, we find $[1/2\ m\ V^2\ n]\ V \times \pi R_M^2 \sim 10^{13}$ watt, with $n = 5\ cm^{-3}$, $V = 400$ Km/sec, and $R_M \approx 15\ R_E$. This figure of $\sim 10^{13}$ watts is two orders of magnitude larger than the EM power flux of $\sim 10^{11}$ watts. Thus, even if a small fraction of it were to penetrate the magnetosphere [say $\sim 1\%$], it would be energetically equivalent to the EM flux. On the other hand, the near numerical coincidence between the solar wind EM power flux and the dissipation by Pedersen currents discussed above, suggests that the EM solar wind flux is the important agent in "driving" high-latitude ionospheric phenomena, in spite of the fact that it is smaller by two orders of magnitude than the kinetic power flux. This view is reinforced by the observed correlation between e.g., currents and electric fields in the high-latitude ionosphere and the solar wind electric field [e.g., Mozer and Gonzalez,

1973; D'Angelo et al., 1976]. Also, it is at least indicative that Akasofu's substorm parameter [Akasofu, 1979] contains no explicit dependence on the solar wind particle density but, rather, depends only on the solar wind $\underline{E}$, $\underline{B}$, and $\underline{V}$. In fact, as shown by D'Angelo and Goertz [1979], Akasofu's parameter can be interpreted as an electromagnetic power flux. In agreement with Bahnsen and D'Angelo [1976], the solar wind in the immediate vicinity of the earth is then viewed as a gigantic voltage generator with varying voltage output, and the solar wind electric field as probably the dominant part of the "driving function" of geomagnetic activity envisaged by Wilcox and Colburn [1972].

b. The simplified model of polar cap electric fields discussed in Section 3 accounts for most features of the global system of high-latitude currents. Since the polar cap electric field is generally directed dawn-to-dusk, and only occasionally and in limited portions of the cap weak dusk-to-dawn fields are envisaged by the model [and observed], it is clear that region 1 and 2 currents should be directed always in the same sense [as is observed]. This feature of the current system is, thus, closely related to the "diode" or "rectifier" mechanism discussed in D'Angelo [1977].

c. As noted by Potemra [1979], "The total amount of current flowing into the ionosphere is always equal to the total current flowing away [within 10%] for every level of magnetic activity." Preservation of current continuity is one of the features of the model presented in this paper.

d. In Fig. 4 the region 2 currents on the dawn side of the earth are directed toward the equatorial plane in both hemispheres, whereas the region 2 currents on the dusk side are directed toward the ionosphere. Continuity is provided by a current W to E in the general region of the inner edge of the plasma sheet. This kind of annular current is to be distinguished from the familiar "ring" current which flows E to W, at substantially lesser radial distances from the earth, and is responsible for perturbations in the horizontal magnetic component at the earth's surface near the equator [e.g., Dessler and Parker, 1959].

Both the "ring" current and our annular current at the inner edge of the plasma sheet are consistent with Eq. 2, which expresses the balance of the plasma pressure gradient by the $\underline{J} \times \underline{B}$ force. The magnitude of the annular current is a function of local time, maximum value being attained near local noon.

e. The near-noon field-aligned current sheets of Wilhjelm et al. [1978] and McDiarmid et al. [1978] have features which are determined by the B_y component of the solar wind magnetic field. The effect of B_z, if at all present, is much less pronounced. With reference to Fig. 6, it is worth noticing that this dependence on B_y alone is not surprising, if the polar cusp is, in fact, a funnel-like feature extending over only 1-2 hours of local time around local noon, rather than a feature spanning a range of local times many hours wide. Reports favoring the funnel-like view of the cusp have appeared recently [e.g., Zaitzeva and Pudovkin, 1976].

VI. CONCLUSIONS

A model of polar cap electric fields previously proposed [D'Angelo, 1977] has been utilized to visualize how high-latitude field-aligned currents are driven by the solar wind generator. Although the solar wind is in all cases the ultimate source of field-aligned currents, two distinct generators are envisaged. One drives the region 1 and 2 currents of Iijima and Potemra [1976a,b] as well as the region A and B currents of Fig. 1. The other generator drives the field-aligned current sheets of Wilhjelm et al. [1978] and McDiarmid et al., [1978].

At least the most prominent features of these two current systems appear to be well accounted for.

APPENDIX

The question may be raised as to whether the simplified model of polar cap electric fields of Section 3 [D'Angelo , 1977] implies the notion of a magnetically open or of a magnetically closed magnetosphere. Although not essential to the development of a model of large-scale magnetospheric electric fields and currents, if the sole aim of the model is agreement with observations, a resolution of the open vs. closed magnetosphere controversy is nevertheless a desirable end. Thus, it is perhaps unfortunate from that point of view, that the simplified model of polar cap electric fields appears to be compatible with both a magnetically open and a magnetically closed magnetosphere. That it is compatible with an open magnetosphere may seem obvious enough that no further comment needs to be made here.

That it is equally well compatible with a closed magnetosphere is shown below.

A magnetically closed magnetosphere is, by definition, one in which at each point on the magnetopause, the normal component of $\underline{B}$, B_n, is equal to zero. A cross-section of this magnetosphere with a dawn-dusk meridian plane is shown in Fig. 1A. We consider again a situation in which $B_z < 0$ and $B_y > 0$. The lines with arrows represent magnetic field lines, both within the magnetosphere and in the

solar wind. Solar wind field lines, such as $\alpha\beta\gamma\delta$ bend at β and γ toward the dayside. The entire solar wind field line $\alpha\beta\gamma\delta$ is in a plane perpendicular to the solar wind $\underline{E}$ field, and is thus an equipotential. This picture corresponds to e.g., Fig. 3 of Fairfield [1976] and seems to be in agreement with observations of the [DC component of the] magnetic field in the magnetosheath. Within the magnetosphere, the earth's polar cap magnetic field lines are "swept back" into either an infinitely long tail [so that cap field lines do not cross the equatorial plane anywhere in the tail] or into a tail of finite length. In the latter case it is assumed that, in the far tail, a given cap field line "loses its identity" in crossing the equatorial plane; electric fields parallel to $\underline{B}$ are allowed, so that the northern portion of a given field line may be at a different potential than its southern portion. The result is, of course, that the northern polar cap is electrically disconnected from the southern cap; their respective potential distributions being directly determined by the solar wind and independent from one another, except insofar as the solar wind determines both.

The regions of the outer magnetosphere with $\underline{B}$ lines antiparellel to the solar wind $\underline{B}$ field correspond to the "closed" regions of Section 3; the "parallel" regions to the "open". In the "parallel" or "open" regions, plasma penetration from the solar wind into the magnetosphere occurs, since $\underline{E} \times \underline{B}$ is directed inward. The flow of this "mantle" plasma then produces the dawn-to-dusk polar cap $\underline{E}$ field.

In the "antiparallel" or "closed" regions, we find that just outside the magnetopause $\underline{E} \times \underline{B}$ is directed into the magnetosphere, whereas just inside the magnetopause, with a dusk-to-dawn $\underline{E}$ field, $\underline{E} \times \underline{B}$ is directed away from the magnetosphere. From the equation

$$\frac{\partial u}{\partial t} + \nabla \cdot \underline{S} = -\underline{J} \cdot \underline{E} \tag{1A}$$

where $u = \frac{1}{8\pi}(E^2 + B^2)$ and $\underline{S} = \frac{c}{4\pi} \underline{E} \times \underline{B}$, it follows that for $\frac{\partial u}{\partial t} \simeq 0$ [stationary conditions], there must be dissipation in the "antiparallel" regions. This is consistent with the idea that the dusk-to-dawn electric field of "closed" regions is, at least in part, attenuated.

It appears that the polar cap $\underline{E}$ field model of Section 3 does not, by itself, particularly favor either a magnetically open or a magnetically closed magnetosphere. Of the two alternatives, which is a better representation of the real magnetosphere has to be decided by other means. Although an open model has been fashionable for many years, recently much evidence has accumulated which favors a revival of the long-neglected closed model [e.g., Stern [1977], Heikkila [1978], Piddington [1979], for reviews and criticism].

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FIGURE CAPTIONS

FIG. 1 A summary of the distribution and flow directions of large-scale field-aligned currents over the northern hemisphere [from Iijima and Potemra, 1976b].

FIG. 2 Schematic diagram of the distribution and flow direction of field-aligned current in the dayside northern hemisphere, illustrating how to reconcile apparently different reports [see text]. Fig. 2a, $B_y > 0$; Fig. 2b, $B_y < 0$.

FIG. 3 Schematic diagram of a cut of the earth's magnetosphere with a dawn-dusk meridian plane, for an observer looking toward the sun. Lines with arrows represent the magnetospheric and the solar wind magnetic field [$B_y > 0$; $B_z < 0$]. The "closed" magnetospheric regions are shown by shaded areas.

FIG. 4 Magnetospheric current distribution and flow direction for the case $B_y = 0$, $B_z < 0$. As in Fig. 3, a schematic diagram is shown of a cut of the earth's magnetosphere with a dawn-dusk meridian plane, for an observer looking toward the sun. Current direction is indicated by heavy arrows or x and · .

FIG. 5 Same as Fig. 4, except now $B_y > 0$, $B_z < 0$. Note the appearance of the "closed" regions [shaded areas].

FIG. 6 A cut of the earth's magnetosphere with a noon-midnight meridian plane. The near-noon current system of Wilhjelm et al., [1978] and McDiarmid et al., [1978] is driven by the voltage difference between S_1 and S_2.

FIG. 1A A cut of the earth's magnetosphere with a dawn-dusk meridian plane [as in Fig. 5]. This figure is used to discuss the compatibility of the simplified model of polar cap E fields with a magnetically closed magnetosphere. The "parallel" [or "open"] regions are indicated by P, the "antiparallel" [or "closed"] regions are indicated by A. In A regions dissipation occurs [see text].

A-G79-202

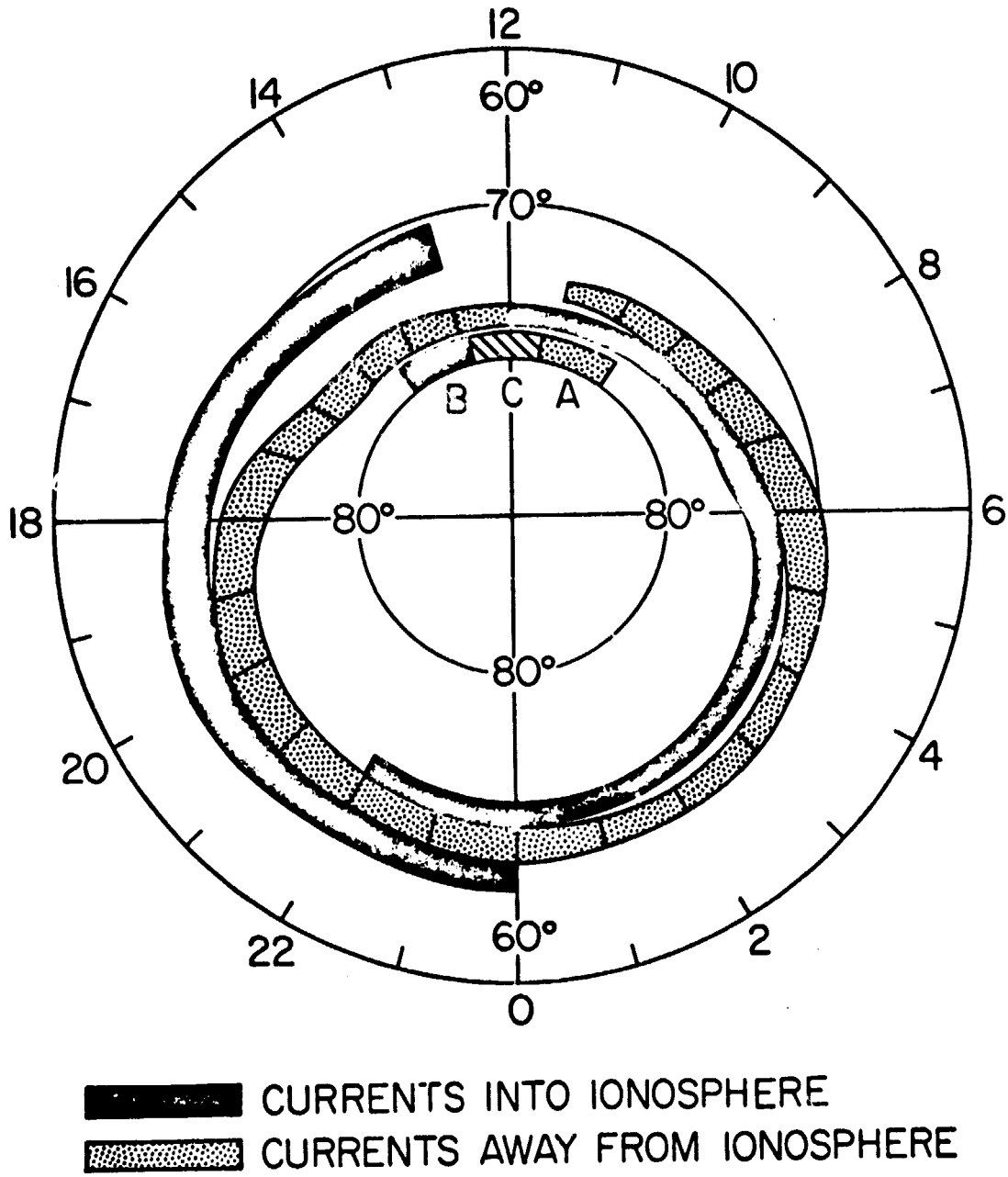

FIG. 1

A-G79-203

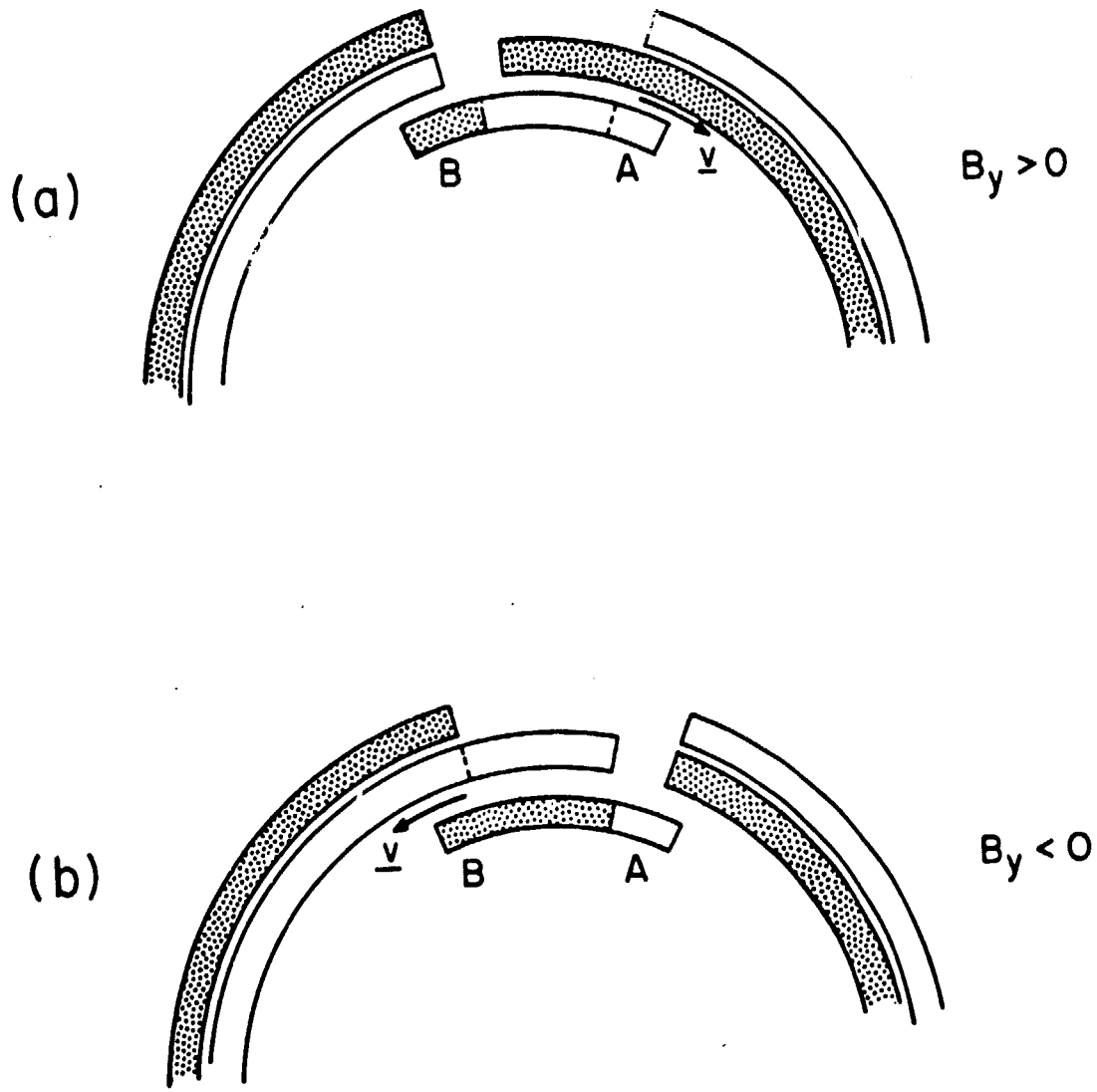

FIG. 2

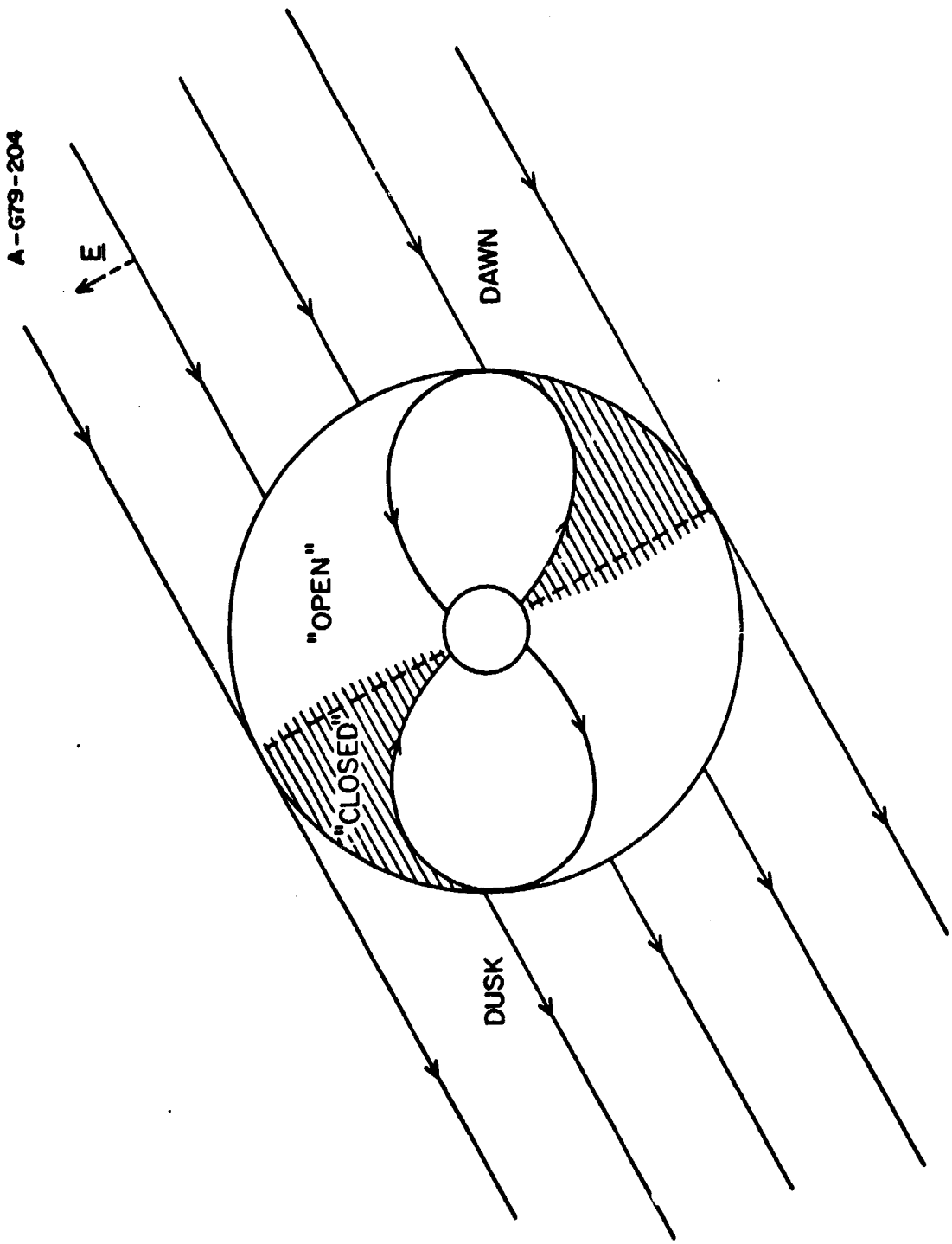

FIG. 3

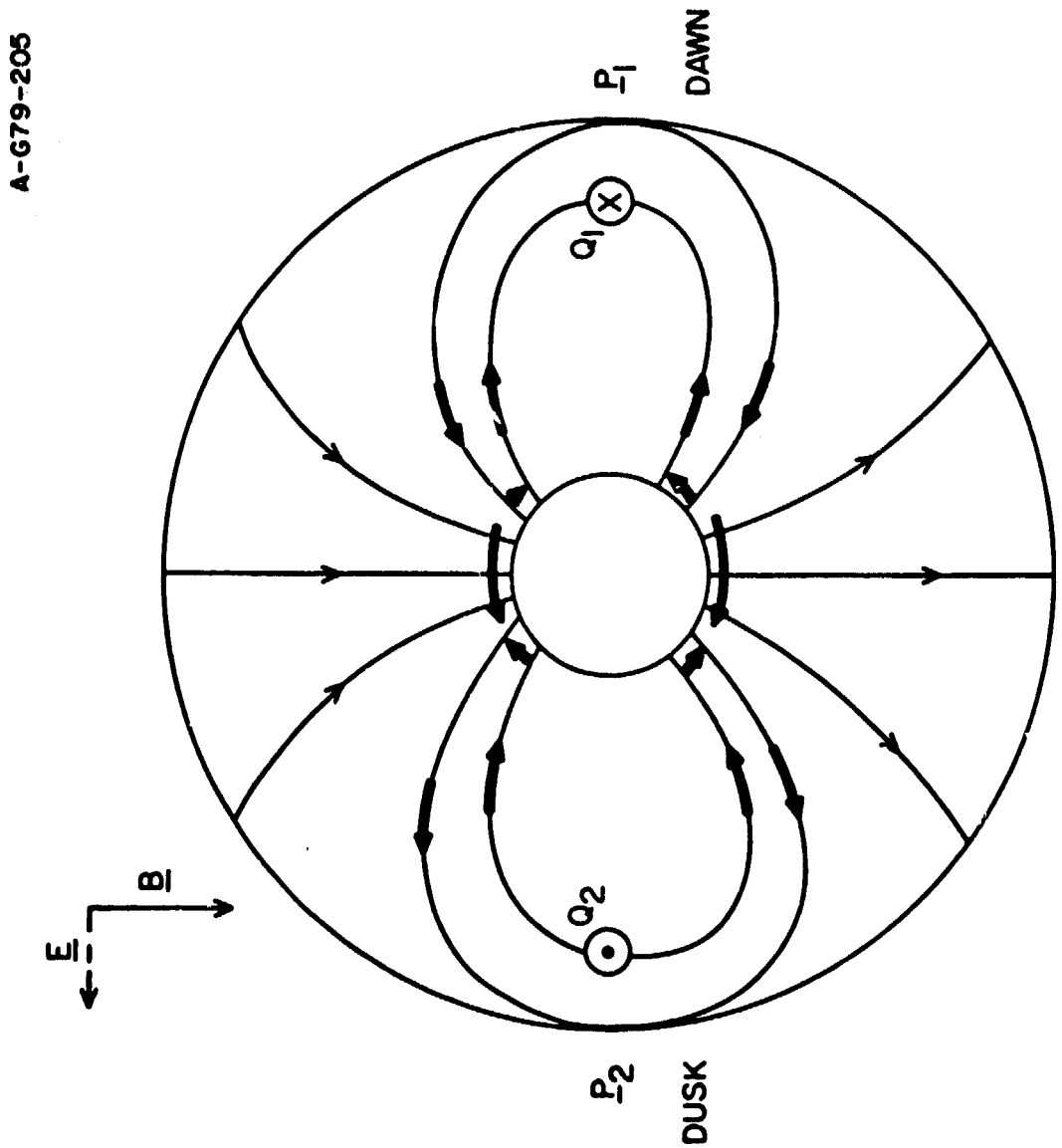

FIG. 4

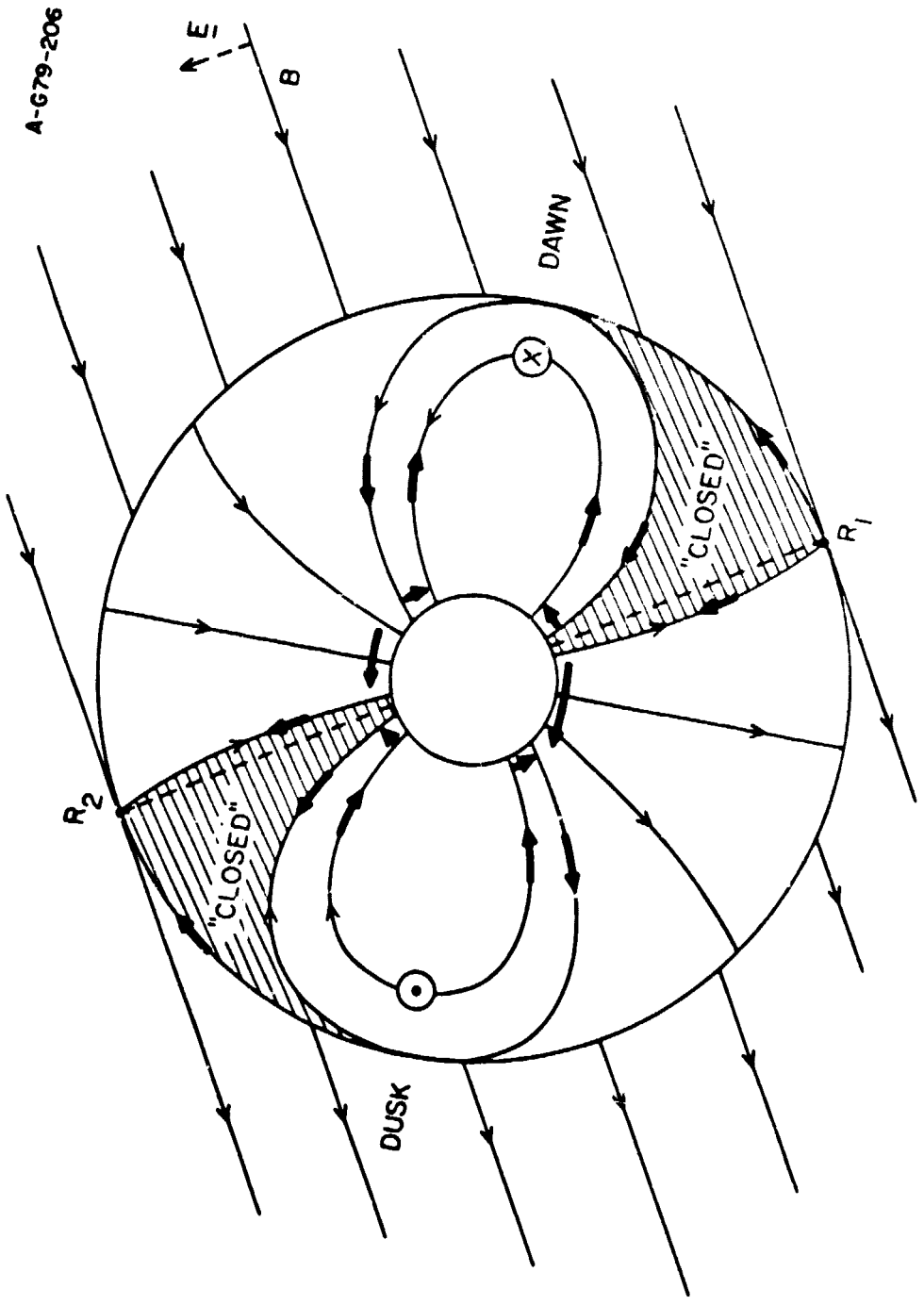

FIG. 5

A-G79-207

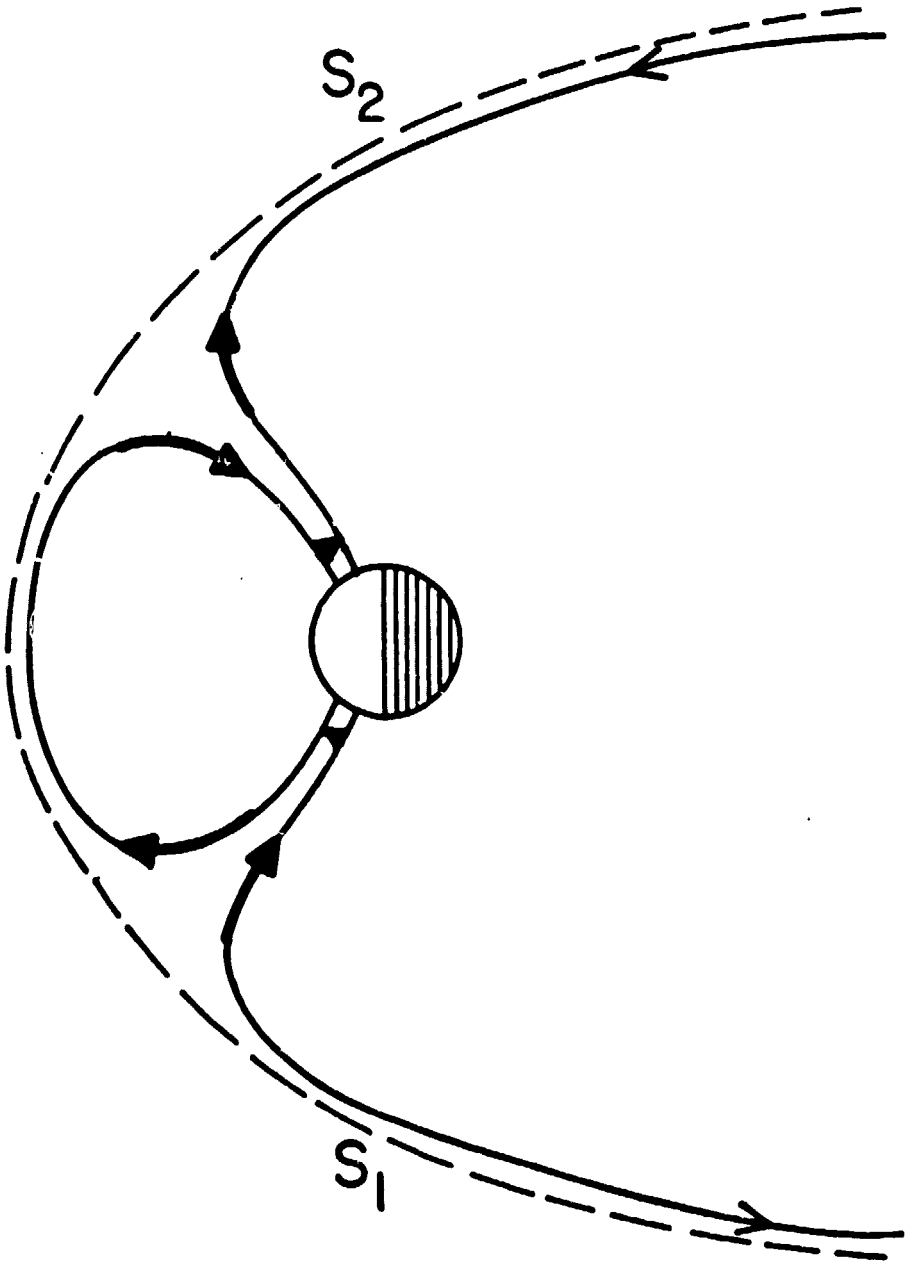

FIG. 6

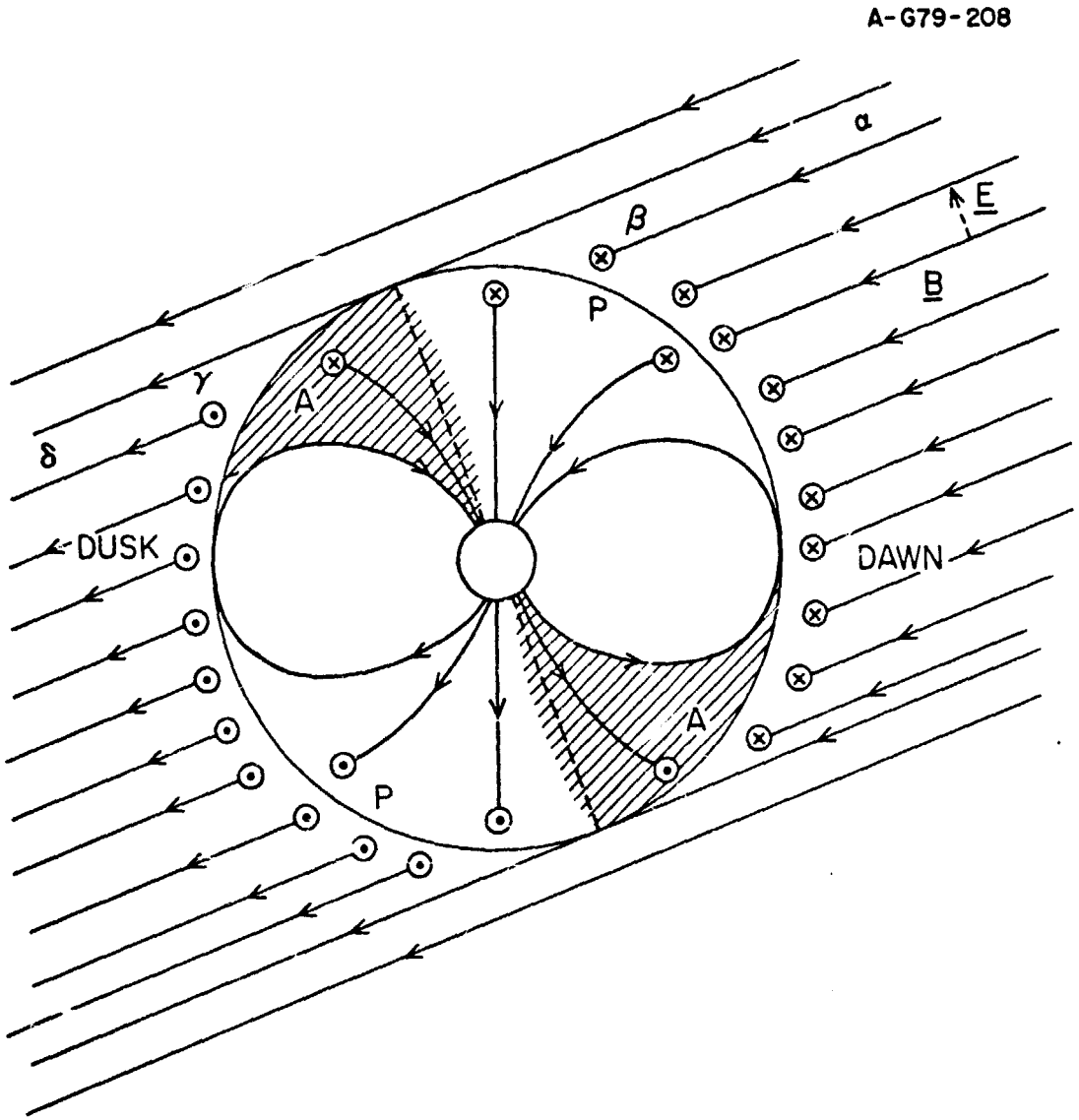

FIG. 1A