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On the origin of the cusp field-aligned currents

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Abstract. A complicated system of field-aligned currents is known to exist in the high-latitude region near noon, associated with the cusp. We suggest that the equatorward part of this system, referred to as the Region 1 field-aligned currents, is caused by the leakage of the field-aligned currents associated with the rotational discontinuities at the dayside magnetopause. The poleward part, referred to as the cusp field-aligned currents, is associated with the tail magnetopause. In this situation, it can be shown that the direction of the field-aligned currents at the magnteopause is controlled by the y-component of the interplanetary magnetic field (B_y). The poleward (equatorward) part of this field-aligned current system is found to flow out of (into) the northern polar ionosphere when $B_y > 0$ and into (out of) the northern ionsophere when $B_y < 0$. This current pattern reverses systematically in the southern polar ionosphere. Therefore, the suggested mechanism can explain qualitatively the observed changes of the cusp current systems. Further, the latitudinal width of the cusp field-aligned current system at the ionospheric altitude is estimated to be 100–400 km, consistent with observations.

Key words: Rotational discontinuity – Field-aligned currents

Introduction

Large-scale field-aligned currents or Birkeland currents in the cusp region have been reported by Iijima and Potemra (1976), McDiamid et al. (1978, 1979), Wilhjelm et al. (1978), Iijima et al. (1978), Rostoker (1980), Doyle et al. (1981) and Bythrow et al. (1982). These cusp field-aligned currents are located between 78° and 81° invariant latitude and between 1000 MLT and 1400 MLT. From a data base that encompassed all orientations of the interplanetary magnetic field (IMF) vector, Iijima and Potemra (1976) found that these currents were determined as flowing into the ionosphere in the post-noon and away from the ionosphere in the pre-noon MLT hours. However, Doyle et al. (1981) showed that at any given time the cusp currents exist only on one side of the noon-midnight axis. In particular, they showed that when the B_y component of the interplanetary magnetic field (IMF) is negative ($B_y < 0$), the cusp field-aligned currents are found to flow mainly into the post-noon sector of the northern polar ionosphere and flow out of the pre-noon sector of the southern polar ionosphere. When $B_y > 0$, the cusp field-aligned currents flow mainly out of the pre-noon sector of the northern polar ionosphere and into the post-noon sector of the southern polar ionosphere.

The earlier and later analyses of both the satellite and ground magnetic-field data over the northern and southern polar regions indicated the existence of a pair of field-aligned current sheets flowing in opposite directions, and also revealed a close correlation between the flow direction of the cusp field-aligned currents and the B_y component of the interplanetary magnetic field (McDiamid et al. 1978, 1979; Wilhjelm et al. 1978; Iijima et al. 1978; Bythrow et al. 1982; Friis-Christensen et al. 1985). The equatorward part of the paired field-aligned current sheets is referred to as the Region 1 field-aligned currents, while the poleward part is referred to as the cusp field-aligned currents. In the northern hemisphere, the cusp field-aligned currents are observed to flow predominantly out of the ionosphere for $B_y > 0$ and into the ionosphere for $B_y < 0$. This current pattern reverses systematically in the southern hemisphere.

Lee and Kan (1979), D'Angelo (1980) and Primdahl and Spangslev (1981) suggested that part of the magnetopause currents may flow into and out of the cusp ionosphere. Lee and Kan (1979) studied the tangential discontinuity, in which B_n, the normal component of the magnetic field at the magnetopause, is zero, and found that the magnetopause currents have a significant field-aligned component. They suggested that part of the magnetopause field-aligned currents can be diverted to and closed through the polar ionosphere. However, the B_y dependence of the field-aligned current was not discussed in their study.

D'Angelo (1980) suggested that the north-south voltage difference across the magnetopause due to the presence of IMF B_y may drive the observed cusp field-aligned currents. Under the assumption of a closed magnetosphere, Primdahl and Spangslev (1981) suggested that the north-south component of the magnetopause current, which is generated to shield the IMF B_y, can be responsible for the cusp field-aligned currents. However, for a closed magnetosphere, it is easy to show on the basis of magnetic flux conservation that the field-aligned currents originating from the magnetopause would be distributed at the ionospheric altitude in a small region with a latitudinal width < 30 km, in contrast to the observed width of 100–400 km. Reiff et al. (1978) and Cowley (1981) suggested that the cusp field-

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aligned currents are due to the closure of the ionospheric currents which are associated with the observed azimuthal plasma flows in the dayside "throat" region.

In this paper we suggest a different mechanism for the generation of the cusp field-aligned currents which can explain qualitatively some of the most crucial aspects of the cusp current system. In our model, the equatorward part of this field-aligned current system, referred to as the Region 1 currents, is caused by the leakage of the field-aligned currents associated with the rotational discontinuities at the dayside magnetopause and the poleward part, referred to as the cusp field-aligned currents, is generated in the tail magnetopause. The flow directions of the field-aligned currents at the magnetopause and of the corresponding cusp field-aligned currents are found to be sensitive to B_y of the IMF. We show also that the flow directions are consistent with the observed patterns for positive and negative B_y values. The latitudinal width of the cusp field-aligned currents is estimated to be 100–400 km. The effects of the field-aligned currents on the plasma flow will also be examined.

Generation of cusp field aligned currents

Magnetopause currents are generated and maintained due to the imposed transition of magnetic fields between the magnetosheath and the magnetosphere. Figure 1 illustrates two possible magnetic hodograms across the dayside magnetopause. The x axis is normal to the magnetopause and directed towards the magnetosheath, while the y and z axes are parallel to the magnetopause. The fields $\mathbf{B}_{mt}$ and $\mathbf{B}_{st}$ are the tangential components of the magnetic field in the magnetosphere and in the magnetosheath, respectively.

For simplicity, the magnetopause will be considered locally as one-dimensional in which all physical quantities depend only on x. The magnetic field at the magnetopause can be written as:

$$\mathbf{B}(x)=B_n\hat{\mathbf{x}}+\mathbf{B}_t(x)=B_x\hat{\mathbf{x}}+B_y(x)\hat{\mathbf{y}}+B_z(x)\hat{\mathbf{z}} \quad (1)$$

where B_n and $\mathbf{B}_t$ are, respectively, the normal and tangential components of the magnetic field, and $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$ and $\hat{\mathbf{z}}$ are unit vectors. Since $\nabla\cdot\mathbf{B}=0$, we have $\mathbf{B}_x=B_n=$constant. If $B_n=0$, the magnetopause is closed and the magnetopause structure is a "tangential discontinuity." If $B_n\neq 0$, the magnetopause is open and can be identified as a "rotational discontinuity."

By substituting Eq. (1) into Ampere's law, the field-aligned component and the perpendicular component of the magnetopause current density $\mathbf{J}$ can be written as:

$$J_{\parallel}(x)\equiv\mathbf{J}\cdot\mathbf{B}/B=\mu_0(B_t^2/B)\,d\theta/dx \quad (2)$$

and

$$J_{\perp}(x)=\mu_0[(dB_t/dx)^2+(B_tB_n/B)^2\,(d\theta/dx)^2]^{1/2} \quad (3)$$

where $\theta\equiv\tan^{-1}(B_y/B_z)$ and μ_0 is the permeability in free space.

It can be seen from Eq. (2) that the magnetopause current may have a field-aligned component if the magnetic field rotates across the magnetopause, $d\theta/dx\neq 0$. The flow direction of the field-aligned current depends on the sense of magnetic field rotation: (i) $J_{\parallel}>0$ if $d\theta/dx>0$, and (ii) $J_{\parallel}<0$ if $d\theta/dx<0$. In fact, the field-aligned component of the magnetopause currents is required to exist if the magnetic fields change direction across the magnetopause. The existence of field-aligned currents at the magnetopause has been shown observationally (e.g. Kaufman and Cahill, 1977; Russell and Elphic, 1978; Sonnerup et al. 1981; Berchem and Russell, 1982) as well as theoretically (Lee and Kan, 1979, 1982; Wang and Sonnerup, 1984).

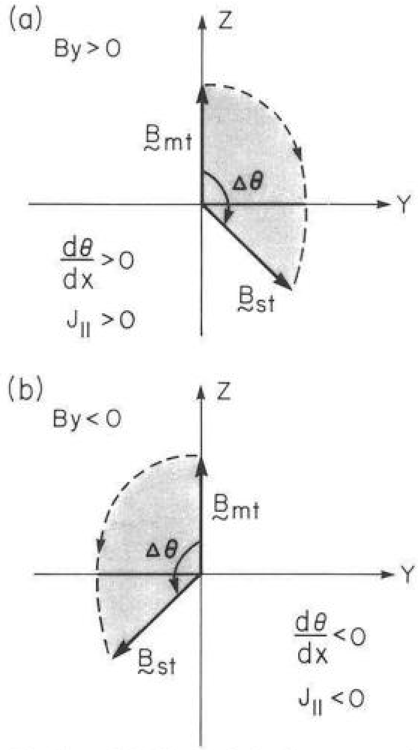

Fig. 1 a and b. Magnetic hodograms at the dayside magnetopause for (**a**) $B_y>0$ and (**b**) $B_y<0$. The x axis is perpendicular to the magnetopause plane (y–z plane). $\mathbf{B}_{mt}$ and $\mathbf{B}_{st}$ are the tangential components of the magnetic field in the magnetosphere and magnetosheath, respectively

We propose that part of the field-aligned currents at the magnetopause will leak, along the geomagnetic field lines, to the polar ionosphere and produce the observed cusp field-aligned currents. The leaking of field-aligned currents from the dayside amgnetopause produces the equatorward part (Region 1) of this system, while the leaking from the tail magnetopause leads to the polward (cusp) part of the field-aligned currents.

It should be mentioned that a rotational discontinuity can be considered as a localized large-amplitude Alfvén wave, across which magnetic fields twist (Lee and Kan, 1982). Since the plasma and field conditions on the two sides of the magnetopause are observed to fluctuate (e.g. Russell and Elphic, 1978), it is likely that part of the highly twisted fields at the magnetopause may propagate as Alfvén waves to the ionosphere, carrying along the field-aligned currents. This is a physical interpretation of the leakage of the magnetopause currents to the ionosphere.

We now discuss the relationship between the flow direction of the field-aligned currents and the B_y component of the interplanetary magnetic field. For this purpose, we note first that the total angle of rotation ($\Delta\theta$) in the magnetic field across the rotational discontinuities at the magnetopause is generally observed to be smaller than or equal to 180°, i.e. $\Delta\theta\leq 180°$. Berchem and Russell (1982) made an extensive study of the rotational discontinuities at the magnetopause based on ISEE 1 and 2 data. They found that the sense of rotation in the magnetic field is controlled by the relative orientation of the magnetosheath and magnetospheric magnetic fields and that the sense of rotation is such as to minimize the total rotational angle $\Delta\theta$ ($\Delta\theta \leqq 180°$). Computer simulation of the rotational discontinuity ($B_n \leqq 0$) by Swift and Lee (1983) also indicated that a rotational discontinuity with $\Delta\theta \leqq 180°$ is stable, while a rotational discontinuity with $\Delta\theta > 180°$ is unstable and tends to evolve into a rotational discontinuity with a rotational angle $\Delta\theta < 180°$. With these facts in mind, we examine field-aligned currents on the dayside and tail magnetopauses.

A) Dayside magnetopause field-aligned currents

We consider the B_y dependence of the field-aligned currents at the dayside magnetopause. For B_y (IMF) > 0, we have $d\theta/dx > 0$ as illustrated in Fig. 1a since the rotational angle $\Delta\theta$ cannot be greater than 180°. It follows from Eq. (2) that $J_\parallel > 0$. In this case, the field-aligned current at the magnetopause is parallel to the magnetic field and flows into the dayside cusp region of the northern polar ionosphere. On the other hand, for B_y (IMF) < 0, we have $d\theta/dx < 0$ and $J_\parallel < 0$ as shown in Fig. 1b. In this case, the field-aligned current is antiparallel to the geomagnetic field and flows out of the northern cusp ionosphere. We identify this field-aligned current as the equatorward part (Region 1) of the field-aligned currents observed by Iijima et al. (1978), McDiamid et al. (1978) and Wilhjelm et al. (1978).

B) Tail magnetopause field-aligned currents

Next, we consider the B_y dependence of the field-aligned currents at the tail magnetopause which are responsible for the poleward part of the observed cusp field-aligned currents. By a similar argument as for the dayside magnetopause, it is found in the northern hemisphere that $J_\parallel < 0$ for $B_y > 0$, and $J_\parallel > 0$ for $B_y < 0$. Therefore, for $B_y > 0$ ($B_y < 0$), the field-aligned current generated at the northern flank of the tail magnetopause is antiparallel (parallel) to the geomagnetic field and flows out of (into) the northern polar ionosphere. The results are thus consistent with observations (McDiamid et al. 1978; Iijima et al. 1978; Wilhjelm et al. 1978; Friis-Christensen et al. 1985). In the southern polar ionosphere, the current pattern reverses systematically.

Global pattern of the cusp field-aligned currents

A global distribution of the cusp field-aligned currents for $B_y > 0$ is schematically shown in Fig. 2, which provides a perspective view of the magnetic fields and currents at the magnetopause and in the cusp region of the northern hemisphere. The currents flow into the cusp ionosphere from the dayside magnetopause and flow away from the ionosphere to the tail magnetopause. It is known that for $B_y > 0$, the interplanetary magnetic flux penetrates into the Earth's magnetosphere mainly from the dawn side of the northern magnetosphere and leaves mainly from the dusk side of the southern magnetosphere (Cowley, 1981; Akasofu and Roederer 1984). Therefore, the cusp field-aligned current density in the northern hemisphere is larger in the pre-noon region than in the post-noon region as shown in Fig. 2. In the southern hemisphere the cusp field-aligned current pattern is reversed, i.e. for $B_y > 0$, currents flow into the

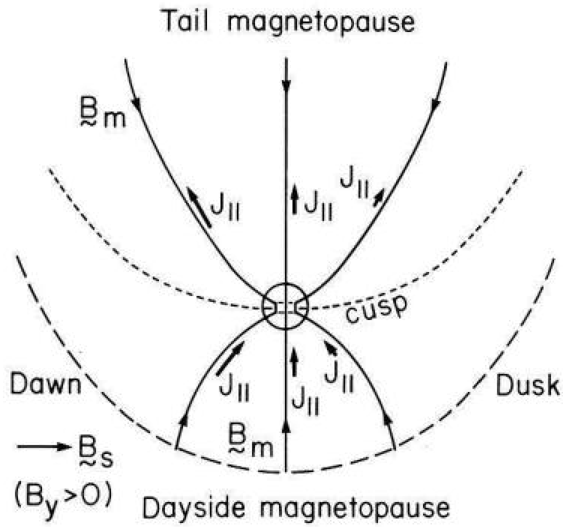

Fig. 2. A global distribution of the cusp field-aligned currents ($J_\parallel$) for $B_y > 0$. The view is from the dayside magnetosheath above the equatorial plane

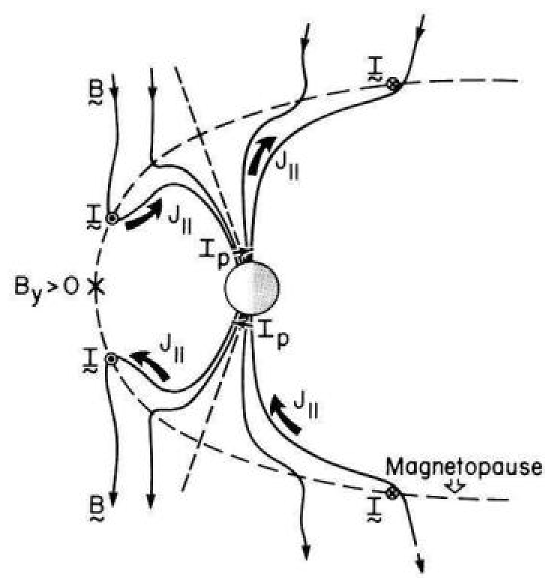

Fig. 3. The cusp current-flow pattern in the noon-midnight meridian plane for $B_y > 0$. $J_\parallel$ is the field-aligned current, I_p is the Pedersen current in the ionosphere, and **I** is the magnetopause current

cusp ionosphere from the tail magnetopause and flow away from the ionosphere to the dayside magnetopause. The cusp field-aligned current density is expected to be larger in the post-noon region of the southern hemisphere than in the pre-noon region of the southern hemisphere.

For $B_y < 0$, the current patterns are systematically reversed and the cusp field-aligned currents flow predominantly in the post-noon (pre-noon) region of the northern (southern) hemisphere.

Note that, in our model, the Region 1 field-aligned current at noon flows toward (away from) the ionosphere in the northern hemisphere for $B_y > 0$ ($B_y < 0$). This result is consistent with the observations by Friis-Christensen et al. (1985).

The current-flow pattern in the noon-midnight meridian plane for $B_y > 0$ is shown in Fig. 3. The poleward and equatorward parts of the cusp field-aligned currents are connected by the Pedersen current I_p in the ionosphere. The equatorward part of the cusp field-aligned current is closed by the dawn-to-dusk dayside magnetopause currents and the poleward part is closed by the dusk-to-dawn tail magnetopause currents. Note that the current closure at the dayside magnetopause in Fig. 3 is different from those presented by D'Angelo (1980) and Primdahl and Spangslev (1981). In their model, the equatorward part of cusp field-aligned currents in the southern hemisphere is directly connected to that in the northern hemisphere through the dayside magnetopause. In our model, on the other hand, the field-aligned currents in the southern hemisphere are not connected to those in the northern hemisphere through the dayside magnetopause.

The latitudinal width of the cusp field-aligned currents in the ionosphere can be estimated as follows. All of the dayside open magnetic field lines can carry the leaked field-aligned currents to the cusp ionosphere. On the other hand, since the anti-sunward boundary-layer plasma-flow velocities at the tail magnetopause are observed to be higher than the local Alfvén speed in the distant tail region with $x \leqq -20\ R_E$ (Akasofu et al., 1973; Rosenbauer et al. 1975), the Alfvén waves will not carry the leaked currents in that region to the ionosphere. The latitudinal width of the cusp field-aligned currents at the ionosphere altitude is just the latitudinal width of the dayside open field lines and near-earth open field lines ($x \geqq -20\ R_E$), which can then be estimated to be 100–400 km, consistent with observations, (Iijima and Potemra 1976; McDiamid et al. 1978, 1979; Wilhjelm et al. 1978; Friis-Christensen et al. 1985). It can also be estimated that a leakage of 5%–20% of the magnetopause currents is sufficient to account for the observed cusp field-aligned current intensity (integrated in the north-south direction) of 0.4 A/m, or the observed total field-aligned current of 2×10^5 A. One the other hand, if the cusp currents are due to the diversion of the north-south magnetopause currents associated with the closed magnetopause, almost all of the magnetopause currents must be diverted to the ionosphere in order to account for the total observed currents (Primdahl and Spangslev, 1981).

The injection of the magnetopause currents to the cusp ionosphere may generate the Pedersen currents, Hall currents and the plasma flows observed in the "throat" region (e.g. Banks et al. 1984). In our model, the strength of the cusp field-aligned currents and the induced plasma flow may depend on the ionospheric conductivity through the reflection of the incoming Alfvén waves which carry the field-aligned currents. For a higher conductivity in the cusp ionosphere, the ionospheric electric field and hence the plasma flow will be smaller; but the field-aligned current will be larger through the enhancement from reflected waves. Thus, our model predicts a smaller "throat" plasma flow and a larger cusp current in the summer hemisphere than in the winter hemisphere. This prediction should be tested by future observations.

Finally, we point out that the cusp currents in our model are different from the "Region O" currents proposed by Heikkila (1984), which are the closure currents of part of the Region 1 currents and flow between open and closed magnetic field lines. In our model, the cusp-region currents flow along open field lines and the equatorward part of the cusp-region currents contributes to the Region 1 currents.

In summary, we suggest that the observed cusp field-aligned current system can be explained in terms of the leakage of the magnetopause currents associated with the rotational discontinuities at the dayside and tail magnetopause. For such a mechanism, the latitudinal width of the generated cusp field-aligned currents at the ionospheric altitude can be estimated to be of the order of 100–400 km, consistent with observations.

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