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The magnetospheric driver of subauroral ion drifts

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Abstract. Subauroral ion drifts (SAID) are narrow layers of intense westward ionospheric flow observed during substorms. We present numerical simulations showing that the combined effect of thermo-electric and convection electric fields in a magnetospheric current sheet—when mapped down to the ionosphere—can account for the westward direction of the ion drift, the width and intensity of the drift speed peak, and the lifetime of SAID. The model can also explain why SAID occur mainly in the pre-midnight sector.

Introduction

Sub-auroral ion drift layers (SAID) are formed in the ionosphere during substorms [*Spiro et al.*, 1979]. These layers have a narrow latitudinal extent and are characterized by an intense westward drift peak. SAID are observed more than half an hour after the onset of a magnetospheric substorm and last generally less than 3 hours. Since SAID often seem to coincide with the ionospheric projection of the plasmapause, previous models have attempted to relate the ionospheric phenomenon to the structure of the space-charge layer (Alfvén layer) at the plasmapause [*Spiro et al.*, 1981; *Anderson et al.*, 1993; *Ober et al.*, 1997]. None of these models, however, identifies the actual electromotive force driving SAID. Nor do they explain why SAID are sometimes detached from the plasmapause, why two or more SAID can be present at the same time, or why SAID occur mainly in the pre-midnight sector [*Spiro et al.*, 1979]. In the present paper we propose an alternative model, which extends the ideas presented in [*Lemaire et al.*, 1997]. We compute the electric structure of a magnetospheric current sheet interfacing hot injected plasma and the cold plasmatrough. Mapped down to the ionosphere, the electric potential profile leads to typical SAID ion drifts. The model also accounts for the lifetime of SAID and their predominant occurrence in the pre-midnight sector.

SAID were discovered by *Galperin et al.* [1973]. They have been identified in ground-based radar data [*Yeh et al.*, 1991], as well as in satellite observations of the ionospheric electric field and ion drift [*Smiddy et al.*, 1977; *Spiro et al.*, 1979; *Anderson et al.*, 1991]. SAID are observed in the F-region or higher, and even in the magnetosphere [*Maynard et al.*, 1980]. SAID invariant latitudes (ILAT) range from 50° to 70° ($L = 2.5 - 8$): between the auroral zone and the plasmapause. The layer is typically 0.5°-1° ILAT wide.

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The drift speed peak exceeds 1 km s^{-1}, corresponding to an electric field of 50 mV m^{-1} or more. The ionospheric processes in SAID are well understood; they have a time scale of a few minutes [*Anderson et al.*, 1991, 1993].

Figure 1 sketches the ionospheric magnetic and electric fields $\boldsymbol{B}_i$ and $\boldsymbol{E}_i$. The westward ion drift is $\boldsymbol{V}_i = \boldsymbol{E}_i \times \boldsymbol{B}_i/B_i^2$ because of the low ionospheric collision rate. Westward drift corresponds to poleward electric field (also in the southern hemisphere). The electric potential drop across SAID is a few to tens of kiloVolts [*Spiro et al.*, 1979; *Smiddy et al.*, 1977]. Downward field-aligned currents flow equatorward of the SAID; Pedersen currents flow through the SAID (a resistive load) in the ionosphere, and upward currents flow on the poleward side. The integrated current per unit length in the azimuthal direction is ≈ 0.1 A m^{-1} [*Smiddy et al.*, 1977; *Anderson et al.*, 1993] and delivers to the ionosphere a power of ≈ 1 kiloWatt m^{-1} along the westward drift band. This power must be generated by a magnetospheric source, since no ionospheric mechanism is known that can produce so much power over such a narrow latitudinal range. Once an SAID is formed, the charge carriers in the F-region are depleted, reducing the ionospheric conductivity, the field-aligned currents, and the power drawn from the source [*Banks and Yasuhara*, 1978; *Anderson et al.*, 1993].

Magnetospheric Current Sheet

We show that a voltage difference sufficient for the formation of SAID is generated across a magnetospheric current sheet interfacing hot injected plasma and the relatively cold plasmatrough. Evidence for the presence of hot injected plasma is found in simultaneous observations of SAID

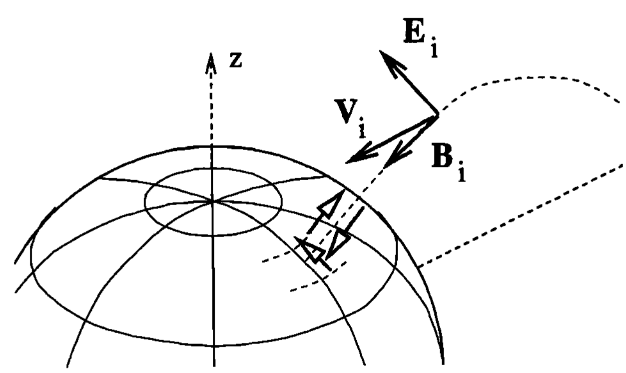

Figure 1. Geometry of the ionospheric magnetic and electric fields $\boldsymbol{B}_i$ and $\boldsymbol{E}_i$, and the drift $\boldsymbol{V}_i$. Westward drift corresponds to poleward electric field. The open-headed arrows indicate the upward and downward field-aligned currents closing through the SAID.

and magnetospheric particle flux dropouts (low density, high temperature regions) [*Anderson et al.*, 1993; *Shiokawa et al.*, 1997]. Other evidence consists of direct measurement of SAID-like electric fields in the magnetosphere [*Maynard et al.*, 1980].

Finite gyroradius effects cause a charge separation in the interface layer. Field-aligned currents flow as a consequence of the thermo-electric potential and try to neutralize the charge separation (see, e.g., [*Willis*, 1970] for a discussion of this process for the magnetopause interface layer). The charge distribution, however, is maintained as charges are continuously replenished from the plasma reservoirs on either side of the current sheet because of plasma motion. The structure of the transition is not essentially modified by the field-aligned currents as long as the injected plasma reservoir is not exhausted and as long as its inward motion continues. This long-lived dynamic equilibrium can therefore be modeled in a first approximation by a tangential discontinuity (TD) equilibrium which ignores the canceling effects of ionospheric discharge and constant replenishment. This corresponds to an unloaded electric circuit: only currents perpendicular to the electric field flow in a (planar) TD, i.e., no energy conversion takes place. The above argument is corroborated by the following order-of-magnitude calculation (cf. [*Roth et al.*, 1993]). With a plasmatrough density of 10 cm^{-3} at $L = 4$, a magnetospheric flux tube with unit cross-section in the equatorial plane contains 10^{15} particles (using an r^{-4} plasmaspheric density profile). Assuming thermal particle transport in the flux tube away from the equator and toward the ionosphere, the maximum particle evacuation rate is 6×10^{11} m^{-2} s^{-1} for 0.75 eV plasmatrough electrons and 2×10^{11} m^{-2} s^{-1} for 1.5 eV protons. A field-aligned potential drop can enhance this rate by an order of magnitude. The density gradient at the current sheet is therefore smoothed on a time scale $> 10^3$ s: the time needed to empty the cold plasma flux tube. Field-aligned currents can alter the structure of the interface only on a longer time scale. (SAID lifetime is indeed of the order of hours.) Cold plasma flux tube evacuation continues as long as the current sheet moves inward. The inward motion will be abruptly decelerated at the plasmapause, where the particle content of a cold plasma flux tube sharply increases: SAID are therefore not expected to propagate very far across the plasmapause.

As the lifetime of the interface is long compared to the ionospheric physico-chemical time scale (a few minutes) and the traveling time of electromagnetic disturbances along a field line with the Alfvén speed (seconds to minutes), the evolution of the interface is so slow that TD equilibrium can be reestablished continuously. For the sake of simplicity, we take the TD to be locally planar, with its normal in the radial direction. We use a 1-D kinetic equilibrium TD model—a simplified version of the more general model discussed by *Roth et al.* [1996]—to compute the electric field in the magnetospheric current sheet. We adopt a right-handed reference frame co-moving with the plasmatrough (x points away from Earth, z to the north).

Because of the low plasma beta in the plasmatrough, the change in magnetic field magnitude and orientation across the interface is rather small. However, a significant velocity shear can exist across the interface. The thermal velocity of plasmatrough ions (1.5 eV protons) near the plasmapause is 20 km s^{-1}. The injected plasma velocity cannot be much larger, or instabilities would develop. As SAID move closer to the ionospheric projection of the plasmapause in the early stages of a substorm [*Yeh et al.*, 1991], the interface approaches Earth. The sunward velocity of the injected plasma and the corotation velocity of the plasmatrough near the plasmapause are anti-parallel at the dusk side, and parallel at the dawn side. Therefore, azimuthal flow shear is largest in the pre-midnight sector.

The structure of the TD depends on the electric field inside the layer. There are two main contributions: a polarization and a convection electric field. Because the gyroradii of plasmatrough and injected ions and electrons are all different, the length scales $\mathcal{L}$ describing the penetration depth of each plasma population across the interface are different too. In the absence of velocity shear, the thermo-electric field peaks inside the layer (Figure 2a), but there is no net potential drop. When a pre-midnight shear flow is present, the convection electric field enhances the electric field peak as in Figure 2b; the convection and the thermo-electric fields tend to cancel in the post-midnight configuration (Figure 2c). The relation between the electric field inside the TD and the orientation of the shear flow is closely linked to the asymmetry in the conditions for which TD equilibria can exist [*De Keyser and Roth*, 1997].

Figure 3 shows the computed structure of a magnetospheric interface at $L = 4$ (where $B \approx 490$ nT) in the pre-midnight sector. The velocity shear is 10 km s^{-1}. The plasmatrough region 0close to the plasmapause (number den-

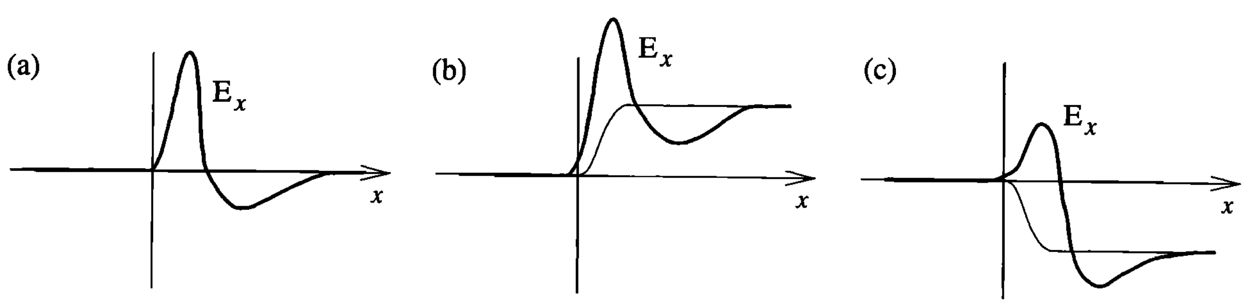

Figure 2. Structure of the current sheet: (a) thermo-electric field (no shear flow); (b) convection (thin line) and total (thick line) electric field for pre-midnight shear flow; (c) the same for post-midnight shear flow.

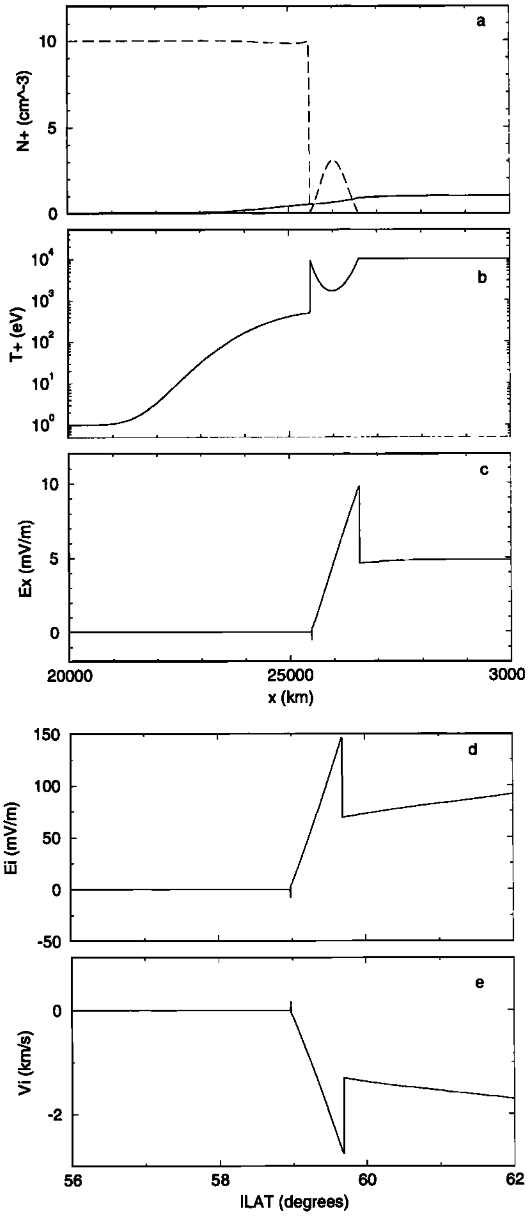

Figure 3. Computed structure of a magnetospheric TD at $L = 4$ in the pre-midnight sector: (a) proton densities (dashed line: plasmatrough, solid line: injected plasma); (b) mean proton temperature; (c) electric field (compare with Figure 2b); (d) ionospheric electric field; (e) drift speed.

sity 10 cm^{-3}) is taken to consist of 1.5 eV protons and 0.75 eV electrons [*Comfort*, 1996]. For the injected plasma we adopt plasmasheet temperatures (10 keV protons, 1 keV electrons) and a number density 1 cm^{-3}. (Numerical experiments confirm that the results are not very sensitive to these choices, as long as the plasmatrough density outnumbers the injected particles, while the latter are much hotter). The order-of-magnitude calculation enables us to estimate the layer thickness: with the $L = 4$ flux tube evacuation rate $< 10^{12}$ m^{-2} s^{-1}, a particle influx of 10^{18} m^{-1} s^{-1} (inward velocity ($\approx$ 10 km s^{-1}) times density (10^7 m^{-3}) times the projected surface of the flux tube in the inward direction (10^7 m^2 per unit length in the azimuthal direction)), implies a thickness of $\gtrsim$ 1000 km. Given the gyroradius ρ^+ of the hot protons of 30 km, we therefore fix the transition length $\mathcal{L}^+ = 50\rho^+$ for both proton populations; we take $\mathcal{L}^- = \mathcal{L}^+/5$ for the electrons ($\mathcal{L}^+/\mathcal{L}^-$ should not be too large to avoid excessively strong, unstable electric field configurations [*Roth et al.*, 1996]). As the reference frame co-moves with the plasmatrough, the electric field is zero there; the convection electric field is positive in the injected plasma region. A strong peak about 1000 km thick is formed inside the layer (cf. Figure 3c). We have similarly computed the structure of a transition with a slightly smaller shear of 6 km s^{-1} in the opposite sense to mimic the post-midnight situration; we found a smooth transition of the electric field between the convection electric field values on either side, as in the qualitative picture of Figure 2c.

Ionospheric Signature

The electric potential in the magnetospheric current sheet can be mapped down into the ionosphere, at least if the magnetospheric conductivity is infinite and/or if the field-aligned currents are small. As the dipolar magnetic field lines converge toward the ionosphere, the electric field across the magnetospheric interface at $L = 4$ is amplified by a factor $2L\sqrt{L-1} \approx 14$. The ionospheric electric field peak now exceeds 100 mV m^{-1} (Figure 3d); the ion drift (Figure 3e) of more than 2 km s^{-1} is westward, concentrated in a region 1° wide, located near 60° ILAT—very typical of SAID.

Discussion and Conclusions

The purpose of this paper was to identify the properties of a magnetospheric current sheet that maps down into the ionosphere as an SAID. We performed simulations of a current sheet interfacing the plasmatrough with hot injected plasma. Due to plasmaspheric corotation the azimuthal shear velocity at the interface is largest in the pre-midnight sector. Additionally, analysis of the internal structure of the interface shows that particularly intense electric fields are generated for the pre-midnight shear flow sense. One of the merits of the present SAID model is the realization that the shear flow controls the size and sense of the potential variations across the current sheet. This can explain the predominant occurrence of SAID in the pre-midnight sector very well. The simulations reproduce the morphology of the SAID drift speed profile (westward orientation, intensity of the drift speed peak, thickness, and location). It is remarkable that both SAID thickness and peak intensity match a single value of $\mathcal{L}^+/\rho^+$.

The model used in this paper ignores several features of the real physical system: the geometry is simplified, curvature effects are not accounted for, the neutralizing effect of field-aligned currents and the associated polarization currents is ignored. Also, we have not incorporated the interaction between the shielding electric field in the inner magnetosphere and the thermoelectric and convection electric fields inside the injected plasma interface.

The SAID model discussed here has an advantage over earlier models that identify SAID with the Alfvén layer, since it can also explain SAID that are detached from the plasmapause. It is also consistent with the observation of energetic particle precipitation from the auroral region down to the SAID latitude [*Anderson et al.*, 1993]: the precipitation traces the region where hot injected plasma is present.

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