Simulation of Discrete Auroral Arcs

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Abstract. In a pair of papers *Lyons* [1980, 1981] demonstrated that, given a potential distribution of sufficient magnitude and small scale-size, applied orthogonal to the magnetic field in the outer magnetosphere, it was impossible to distribute that potential around a circuit that threaded the ionosphere while maintaining current continuity without a major portion of the available potential appearing parallel to the magnetic field. The field-aligned electric field would accelerate electrons downwards into the atmosphere to produce discrete aurora. This paper addresses the origin of the magnetospheric potential distribution in terms of the electric field structure that arises across the interface between differing plasma populations in the magnetosphere. Numerical simulations of such structures are presented that display both the scale-size and available electric potential that, according to Lyons, will lead to parallel electric fields and the creation of discrete aurora. It is suggested that the source of discrete aurora is associated with the interface between differing plasmas in the magnetosphere.

1. Introduction

The realization during the 1970's that ionospheric currents were connected to magnetospheric processes by field-aligned currents [*Iijima and Potemra,* 1976] and that auroral electrons were likely accelerated by parallel electric fields [e.g. *McIlwain*, 1960, *Evans*, 1974] provided the motivation for *Lyons* [1980] to model the self-consistent electric fields and currents around a circuit that included a magnetospheric generator and the ionosphere. Assuming a V-shaped potential distribution at high altitude and field aligned current flow governed by the voltage-current relationship given by *Knight* [1973], Lyons showed that, in general, the magnetospheric potential distribution could not be distributed around a circuit through the ionosphere and maintain current continuity without a major portion of that potential being distributed along the magnetic field linking the ionosphere and the magnetosphere. In a second paper, *Lyons* [1981] utilized actual observations of ionospheric level electric fields and precipitating electrons measured by rocket instruments during a transit over an auroral arc. The observed electron energy spectrum allowed an estimate to be made of the field-aligned potential drop that, when coupled with the observed electric fields, permitted a description to be made of the electric potential distribution in the magnetosphere, above the region of parallel electric field (Figure 1). The auroral electron observations also allowed estimates to be made of the number density and temperature of the electron sources feeding the auroral acceleration, parameters needed for the Knight current-voltage relation. Lyons applied his earlier analysis to this physical situation and modeled an ionospheric level electric field distribution using only the magnetospheric potential distribution and source plasma properties as inputs. The excellent comparison with observations is also shown in Figure 1. Additional comparisons between modeled electron energy fluxes and those actually observed were also excellent.

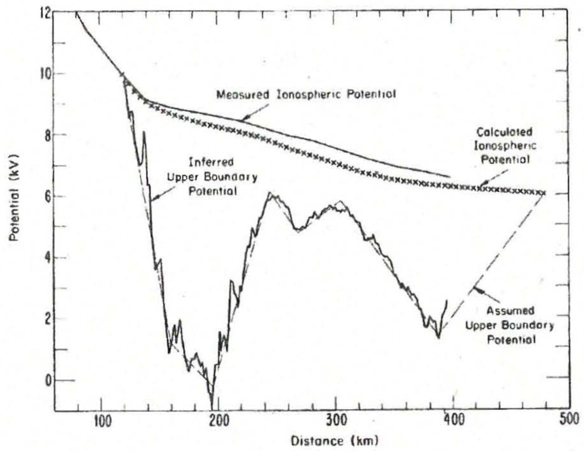

Figure 1. The high altitude potential distribution was inferred from rocket measurements at low altitude. That distribution was used to model the potential distribution around a circuit linking the ionosphere. Both the modeled low altitude electric field and the parallel potential differences required to insure current continuity agreed well with observations [*Lyons*, 1981]

While providing a compelling argument for the necessity for parallel electric fields, Lyons did not address the origin of potential distributions at high altitude having the appropriate properties that is the subject of this paper.

2. Potential Structure at Plasma Boundaries

It is instinctively obvious that a space charge separation (and associated potential distribution) should exist across the interface between different plasma populations in the presence of a magnetic field. This is because the gyro-motion across the interface of charged particles from one population cannot be exactly balanced by gyro-motion of particles from the other. There is also observational evidence that discrete aurora occur at the boundary between different plasma populations in the magnetosphere [e.g. *Lyons and Evans*, 1984]. These facts motivated *Roth et al.*, [1993] to apply a kinetic approach to model the space charge, electric field, and potential distribution across the interface between magnetized plasmas to ascertain whether such distributions had the properties that would lead to major field-aligned potential differences according to the Lyons picture.

The approach to the simulation followed that originally formulated by *Sestero* [1964] for plasma sheaths in the laboratory and further developed and applied by, for example, *Lemaire and Burlaga* [1976], *Roth* [1976], *Lee and Kan* [1979], and *Roth et al.* [1996] to tangential discontinuities in space plasmas.

For illustrative purposes, *Roth et al.* [1993] choose a simple physical situation of two plasma populations of differing temperatures and densities that were specified at large distances from a localized interaction region ($x = +\infty$ and $x = -\infty$). The plasma properties were assumed independent of the y and z coordinates and the boundary between the plasmas was assumed to be centered at the $x = 0$ plane. A magnetic field in the z direction was assumed at $x = -\infty$. This defines a one-dimensional problem.

In the model, the plasma at $x = -\infty$ was assumed to be high temperature and dense, similar to a plasma sheet population, while at $x = +\infty$ the plasma was assumed to be cooler and less dense, similar to that found in the magnetotail lobe. The specific plasma properties for the simulation were proton and electron number densities of 0.5 cm^{-3}, electron temperature 2500 eV, and proton temperature of 12000 eV at $x = -\infty$ (plasma sheet) and proton and electron number densities of 0.15 cm^{-3}, electron temperature 800 eV, and proton temperature of 3000 eV at $x = +\infty$ (magnetotail). The magnetic field at $x = -\infty$ was assumed 40 nT in the +z direction.

The numerical simulation solved for the space charge distribution, electric field structure and potential structure across the plasma interface self-consistently with the motion of the charged particles in the electromagnetic fields. The solution was constrained by the assumption that the scale-size of the interface in the x dimension was governed by the mean of the proton gyro-radii determined from the two proton temperatures. The simulation also permitted an externally imposed, large-scale, potential difference across the system from $x = -\infty$ to $x = +\infty$, such as might arise from the interaction of the solar wind passing Earth in the presence of the geomagnetic field.

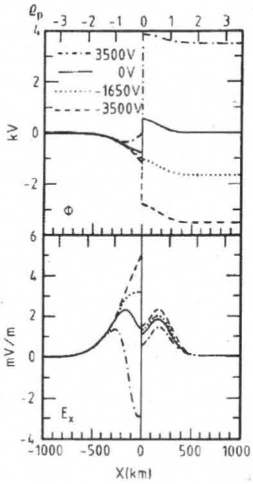

Figure 2. Modeled electric field and potential distributions for three cases of externally imposed potentials and for no external potential [*Roth et al.*, 1993].

Figure 2 displays the electric field and potential distribution across the plasma interface for four choices of an externally applied potential difference. The left panels are the distributions over proton gyro radii scale-lengths while the right panels are for the smaller electron gyro radii scale-lengths. The solid curve in each panel is the model result when there is no externally applied potential and show, for these plasmas, a total available potential difference of about 2000V due only to a 'thermoelectric' charge separation. Interestingly, when the simulation includes the presence of a large-scale externally applied potential, that potential difference is concentrated across the plasma interface rather than distributed uniformly through the system, which greatly increases the potential difference over small dimensions. Both the magnitudes of modeled potential differences, and the dimensions over which they are distributed (≈100s km at high altitude corresponding to ≈10s km at ionospheric level) are sufficient according to the Lyons picture to give rise to large parallel potential differences and electron energization and production of aurora.

The space charge imbalances responsible for the electric field structure are modest; of order 1 in 10^6 on the ion gyro-radius scale and 1 in 10^2 on the scale of the electron gyro-radius. It might be thought that such small space charge densities might easily be discharged and the electric field distributions quickly disappear. However, the space charge separations are a consequence of the plasma boundary and will continue to exist until that boundary is eroded away by other processes.

While these results were very encouraging, the orientation of the plasma interface with respect to both the magnetic field and any externally applied potential may not have been appropriate to a realistic magnetospheric geometry.

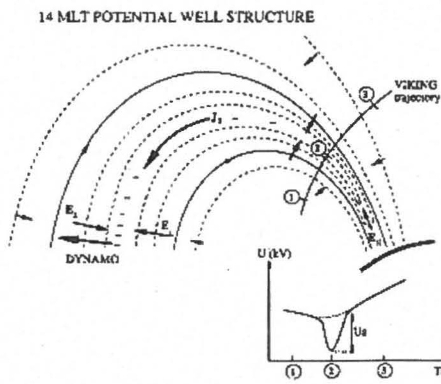

Figure 3. Electric field and potential structure observed in the afternoon sector by the Viking satellite [*Lundin, et al.,* 1995].

Roth and De Keyser [2001] recently have modeled a more realistic magnetospheric plasma and field geometry appropriate for the dusk flank magnetosphere, based upon Viking observations [*Lundin, et al.,* 1995] of electric fields and plasma distributions in the afternoon sector. The Viking observations, displayed in Figure 3, showed an electric potential well at high altitude that was co-located with auroral precipitation that was observed at the satellite. Electric field measurements on board the satellite provided the potential distribution shown in the insert. The change of slope in the potential distribution from one side of the precipitation region to the other indicates sunward plasma flow at lower latitudes and anti-sunward flow at higher latitudes. The region of particle precipitation was located at the shear in plasma flow.

In their simulation Roth and De Keyser assumed that the lower latitude flux tubes were filled with low density, high temperature magnetospheric plasma. At higher latitudes the plasma was assumed to be cooler and denser, typical of the low-latitude boundary layer (LLBL). The bulk flow velocity of the magnetospheric plasma was assumed to be small, while in the boundary layer the flow was strong and anti-sunward. Having set the boundary conditions at large distances from the plasma interface, Roth and De Keyser self-consistently modeled the charge density, electric field, and potential distributions across the plasma interface.

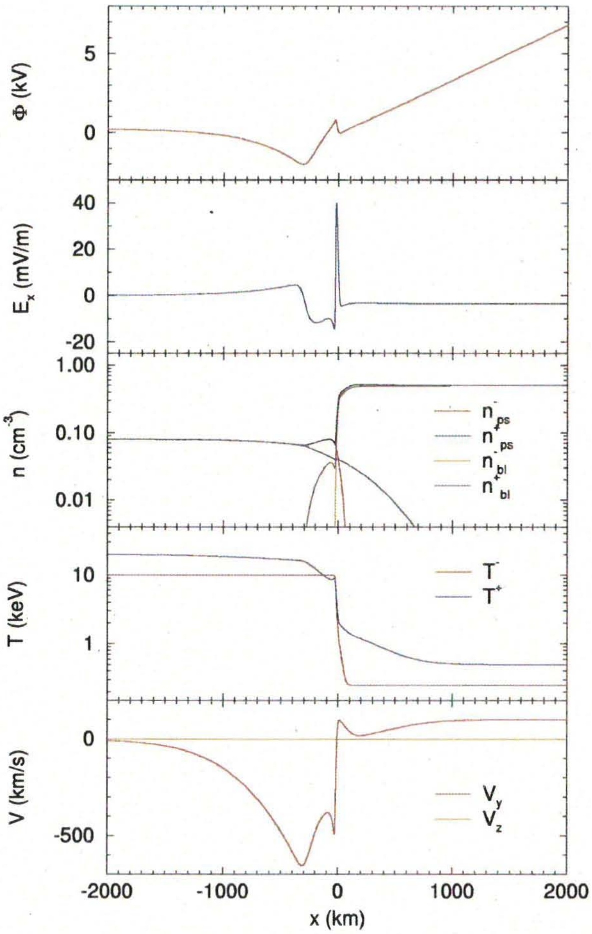

Figure 4. Simulation results for the potential and plasma boundary geometry observed by Viking. The x axis points duskward, the y axis points tailward, while z completes the right-handed reference frame [*Roth and De Keyser*, 2001].

The simulation results are shown in Figure 4. The left side of each panel refers to the magnetosphere and the right side to the LLBL with the asymptotic values in plasma number density, temperature, and flow velocity being the boundary conditions (a 20 nT magnetic field at the dusk flank magnetospheric boundary has been assumed). The top two panels display the modeled potential and electric field distributions across the plasma interface. The total potential difference across the interface reaches nearly 4000 V over a scale length of about 300 km set by the gyro radius of the denser LLBL proton population (third panel). As in the earlier example, the magnitude of the available potential difference and the scale size, which maps to about 10 km in the ionosphere, are such that according to Lyons a major portion of that potential must appear along the magnetic field.

3. Discussion and Conclusions

Numerical modeling has demonstrated that large electric potential differences develop at magnetospheric plasma convection interfaces between magnetized plasma populations of different properties because of the thermoelectric effect. If in addition a large scale, external potential is applied across the system, the magnitude of the potential jump across the interface may be significantly increased because that external potential difference can be concentrated at the interface. For plasma populations typical of the outer magnetosphere the modeled potential differences are sufficiently large and the scale lengths normal to the magnetic field over which the potentials are distributed sufficiently small that a major portion of the available potential must be distributed along the magnetic field connecting to the ionosphere in order to obtain a divergence free current system. Those parallel potential differences are capable of accelerating electrons into the atmosphere to create aurora.

Boundaries between different plasmas are ubiquitous in the outer magnetosphere and it is proposed that the potential differences that arise across those interfaces are the source of electromotive force (EMF) that sustains parallel electric fields, accelerates electrons to auroral energies, and creates discrete auroral arcs. As a corollary, then, discrete auroral arcs in the ionosphere map to locations of plasma discontinuities in the outer magnetosphere.

The results presented here describe a one dimensional situation, one that is time stationary, and does not include currents flowing across the plasma interface. While successful in describing a likely source of EMF required for discrete aurora, there are several areas that require further research. One area is the time evolution of the system. As pointed out, the charge separations and electric fields across plasma interfaces arise because of the existence of the boundary and will disappear only as the boundary is eroded. However, the time behavior of the system must be addressed. A second area must is the three-dimensional current circuit including current flow through this source of EMF, along the magnetic field line to and from the ionosphere, and through the ionosphere. This second step will necessarily involve unraveling those subtle processes that insure current closure at all points around the circuit.

Acknowledgments

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