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Preliminary Study of the Dynamics of High Latitude Nuclear Plumes

J.A. FEDDER AND J.G. LYON

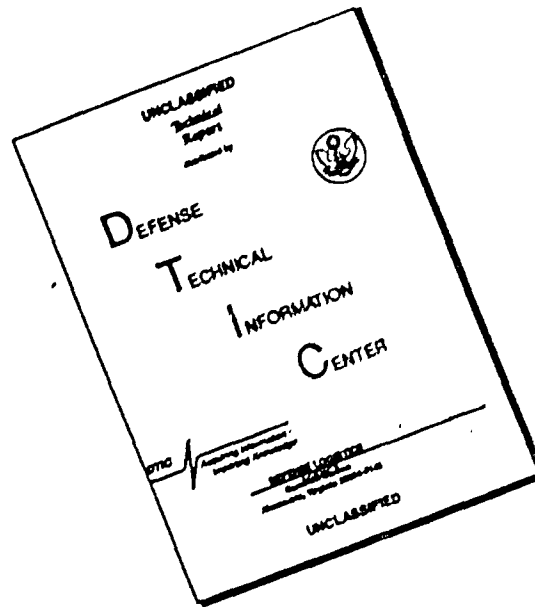
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This memorandum reports the first results of a preliminary study of the late time behavior of a HANE plasma plume at high-latitude and its interaction with the dynamic plasma processes existing there. The plume is modeled as a region of extremely high ionospheric conductivity. The results demonstrate that the HANE plasma conductivity enhancement polarizes so as to exclude the high velocity plasma convection and therefore does not take an active part in the energetic high-latitude plasma processes. <i>... of the late time plume evolution of HANE plasma plumes</i>					
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PRELIMINARY STUDY OF THE DYNAMICS OF HIGH LATITUDE NUCLEAR PLUMES

I. INTRODUCTION

The late time remnant of a High Altitude Nuclear Explosion (HANE) is a region of greatly enhanced plasma density in the ionosphere and extended along geomagnetic field lines into the magnetosphere. This remnant, commonly called a nuclear plume, extends hundreds of kilometers perpendicular to the magnetic field and 10's of thousands of kilometers along the field. The plasma density in the plume is typically 10^6 to 10^8 cm^{-3} and can be highly structured perpendicular to the magnetic field. These nuclear plumes, which can exist for 10 hours or more, constitute a serious threat to radio and microwave communication systems which rely on space based assets. At low and mid geomagnetic latitudes, the late time motion and evolution of nuclear plumes are reasonably well understood. They are affected primarily by gravity which causes the plasma to slowly fall and by thermospheric neutral winds which can cause the plume to move perpendicular to the magnetic field at 10 to 100 m sec^{-1} . This relatively slow motion is typical of all ionosphere and magnetosphere plasma at low and mid latitudes.

The situation at high latitudes, the auroral regions and polar caps, is substantially different. Here the ionosphere and magnetosphere plasma is electromagnetically connected to the solar wind. The convection is responsible for large scale energetic current systems, the auroral particles which precipitate into the ionosphere, and the plasma convection, high velocity plasma flow at speeds which can exceed 1 km sec^{-1} . Two natural and important questions immediately arise. How do these dynamic polar processes affect nuclear plumes? How do nuclear plumes affect the polar plasma processes and the connection of the earth's magnetosphere to the solar wind?

We have recently developed a simulation model for the earth's magnetosphere and its interaction with the solar wind. The simulation model allows the theoretical study of the polar currents, the auroral plasma, and the plasma convection and how these natural processes are affected by the solar wind. In a recent publication [Fedder and Lyon, 1987] we have discussed the solar wind-magnetosphere-ionosphere current-voltage relationship. The simulation model also can allow, with proper alteration, the study of HANE plasma at high latitudes.

In this paper we report the results of a preliminary study of HANE plasma dynamics at high latitudes. The HANE plasma is modeled as a region in the polar ionosphere with greatly enhanced conductivity. We report on the modification which this enhancement causes in the polar currents and the plasma convection. We discuss the implications of these results for high latitude HANE dynamics. Finally, we suggest future research studies to further elucidate the problem.

II. MODEL

The simulations are based on the ideal MHD equations which are used to describe the solar wind and the outer (beyond $3.5 R_e$) magnetosphere. They are given as follows.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \underline{v}) = 0 \quad (1)$$

$$\rho \frac{\partial \underline{v}}{\partial t} + \rho (\underline{v} \cdot \nabla) \underline{v} + \nabla p = \underline{j} \times \underline{B} \quad (2)$$

$$\frac{\partial \varepsilon}{\partial t} = - \nabla \cdot (\varepsilon + p) \underline{v} + \underline{j} \cdot \underline{E} \quad (3)$$

$$\frac{\partial \underline{B}}{\partial t} = - \nabla \times \underline{E} \quad (4)$$

$$\mu \underline{j} = \nabla \times \underline{B} \quad (5)$$

$$\underline{E} + \underline{v} \times \underline{B} = 0, \quad (6)$$

where the symbols have their common usage. For the magnetospheric-solar wind region of interest the major error in these equations is the neglect of the so-called Hall term, $m/\rho e(\underline{j} \times \underline{B})$, on the right hand side of (6). These equations are solved as an initial value problem to a quasi-steady state for a given solar wind condition.

Our recent simulations have included a number of innovations. First, the development of a fully-nonlinear, high-accuracy algorithm for solution of the MHD equations [J.G. Lyon, manuscript in preparation]. Second, the use of a spider web numerical grid which is rotated around the sun-earth axis to provide a 3-dimensional cylindrical mesh which gives

high resolution in important regions (i.e., the dayside magnetopause, the polar open field line region). Third, the inclusion of a model for the conducting ionosphere, which provides a physical inner boundary to the MHD system. Specifically, the ionosphere is modeled electrostatically,

$$\nabla \cdot \underline{\underline{\Sigma}} \cdot \underline{\underline{E}} = J_{||}. \quad (7)$$

The parallel current density, $J_{||}$, is calculated at the inner boundary ($3.5 R_E$ geocentric radius) of the MHD mesh. It is mapped along dipole field lines to the ionosphere where the electric field, $\underline{\underline{E}}$, is computed using a conductivity model for the ionosphere. The electric field is then mapped outward to the inner boundary where it is used as a boundary condition for both the momentum balance equation and for Faraday's Law. The system of equations (1) thru (7) form a closed set with the conductivity, $\underline{\underline{\Sigma}}$, provided. They also constitute a realistic, restricted physical model for magnetosphere-ionosphere coupling. The main effects ignored are the Alfvén propagation time from $3.5 R_E$ to the ionosphere, the possible existence of field aligned potentials, and the enhancements to conductivity created by precipitating auroral particles.

For the results presented here we have used steady solar wind conditions with density, $n = 5 \text{ cm}^{-3}$, velocity, $V = 400 \text{ km sec}^{-1}$, temperature, $T = 10 \text{ eV}$, and IMF, $B = 5 \text{ nT}$ southward. We have also used a uniform ionospheric conductance 2.5 mho . The HANE plasma plume is modeled as an enhancement of the ionospheric conductance to 1000 mho with a horizontal extent in the ionosphere of about 500 km . The magnetosphere was allowed to achieve a quasi-steady state for the given solar wind and uniform conductance before introduction of the HANE conductivity enhancement.

III. RESULTS

The results of the simulation study are demonstrated with contour plots of the high latitude field aligned currents and the polar electric potential. Figure 1 shows the currents and potential before introduction of the high conductivity region. The currents in the left plot show the Region 1 and Region 2 Birkeland current systems. The Region 1 currents are out of (positive) the ionosphere in the afternoon-evening and into (negative) the ionosphere in the morning. The Region 1 currents are the driving currents for the polar convection and originate in the solar wind-magnetosphere dynamo as discussed in Fedder and Lyon [1987]. The Region 1

current sheets also delineate the boundary between open magnetic field lines connecting to the solar wind and the earth's closed field lines at lower altitudes. The right plot in Fig. 1 shows electric potential contours which are also flow lines for the plasma convection. The flow is distributed uniformly across the polar cap in the antisolar direction (noon to midnight) and returns toward the dayside as lower latitudes. The antisolar flow occurs essentially on open magnetic field and sunward flow on closed field.

For this preliminary study the conductivity enhancement, simulating the HANE plume plasma, was inserted in the northern polar ionosphere just poleward of the afternoon-evening Region 1 current sheet at 77° magnetic latitude and at an hour angle of 14:30. Figures 2, 3 and 4 show the results in a temporal sequence during the continuing simulation. There are a number of notable features in the results. First, the Birkeland current patterns are essentially undisturbed by the introduction of the HANE conductivities. Second, the potential patterns and plasma convective flow avoid the region of enhanced HANE conductivity. Third, after a very quick adjustment to the HANE conductivities lasting less than 5 minutes the currents and flow become quasi-steady and are essentially unchanged for the next 15 minutes. A final notable feature seen in both the north and south polar regions, Figs. 4 and 5, is the dramatic shift of high speed antisolar plasma convective flow from the afternoon side of the polar region toward the morning side. We will discuss these features and their physical cause in the following section.

IV. DISCUSSION AND CONCLUSIONS

The results presented in the previous section allow us to begin to form some tentative conclusions concerning the dynamics of HANE plasma plumes and their interaction with the high latitude environment. The apparent absence of major morphological changes to the Birkeland current patterns shown in Figs. 2 - 5 show that the HANE conductivity enhancement does not effectively couple to the solar wind magnetosphere dynamo. This result is consistent with our previous results in Fedder and Lyon [1987] which showed that increasing polar conductivities reduce the power delivered by the solar wind to the magnetosphere-ionosphere. There are some perturbations to the polar current pattern along the edges of the plume but both the current density and the total current are much smaller than that in the Region 1 current system.

The changes to the potential pattern and the convective flow of plasma in the polar region is much more remarkable. The results demonstrate that the plume polarizes so as to exclude the polar electric fields. This leads to the plasma convection flowing around the conductivity enhancement. Inside the enhancement the electric field and therefore the plasma speed perpendicular to the geomagnetic field is more than an order of magnitude less than that outside. This result indicates that HANE plumes should be expected to evolve only very slowly at high-latitudes and not participate in the general plasma convective flow. This is an important result since it indicates that high latitude HANE plasma plumes should be very long lived and should decay very slowly owing primarily to the effects of gravity and plasma recombination in the ionosphere. Also, because of the strong shielding of the convective electric field one would not expect plumes to structure by the gradient drift instability. On the other hand, the strong velocity shear which will occur at the plume boundary could lead to erosion of the plume via the Kelvin-Helmholtz instability (Keskinen et al., 1987).

The final notable result is the shift of strong convective flow from the afternoon side of the polar cap toward the morning side as demonstrated in both Figs. 4 and 5. This result indicates that, although the conductivity enhancement does not couple strongly to the solar wind-magnetosphere dynamo, the normal coupling of the ionosphere to the dynamo is changed. The change occurs by causing the dayside magnetic reconnection region, the source of the dynamo, to move towards the morning side of the magnetosphere and may also involve changes in the external shape of the magnetosphere. A complete understanding of the detailed nature of these changes will require further study.

There is one other effect not mentioned in the results section that deserves discussion. If one examines the temporal sequence, Figs. 1 through 4, one notices a gradual decrease in both the polar cap potential and the intensity of the Region 1 Birkeland currents. More careful examination also indicates a shrinkage in the area of the polar cap, the open field line region, and a decrease in the width of the dayside anti-sunward flow. Whether this decrease is caused by the HANE conductivity enhancement or by a quasi-steady oscillation of the magnetosphere system is not yet clear and will require further study. Nevertheless, it is consistent with our previous results showing reduced efficiency for the solar wind-magnetosphere dynamo in the presence of enhanced polar ionosphere conductivities.

The results and conclusions here are preliminary and therefore tentative for a number of reasons. First, the model of the HANE plasma plume as a conductivity enhancement ignores the great volume of HANE plasma extended along the geomagnetic field into the magnetosphere. This plasma at great altitudes could lead to additional effects not anticipated in this report. Second, the numerical resolution in the polar ionosphere is rather coarse and the plasma conductivity enhancement occupied essentially a single numerical cell. Higher resolution simulations are necessary to confirm these preliminary results. Third, the results presented here consider only a single HANE plasma plume at one location in the polar region. Additional simulations are required to investigate the effects of HANE plasma plumes in different locations and the effects of multiple HANEs in the high latitude ionosphere-magnetosphere. Finally, the conductivity enhancement in this simulation was held fixed in space throughout the calculation. The motion of the HANE plume could become important over temporal scales of an hour or more as it drifts and distorts, however slowly, in the reduced high latitude convection field. In the future, we intend to remove these previously mentioned limitations of the current simulation model and to thereby improve the accuracy of the results.

ACKNOWLEDGMENT

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Northern Hemisphere step=15000 time= 5.968E+03

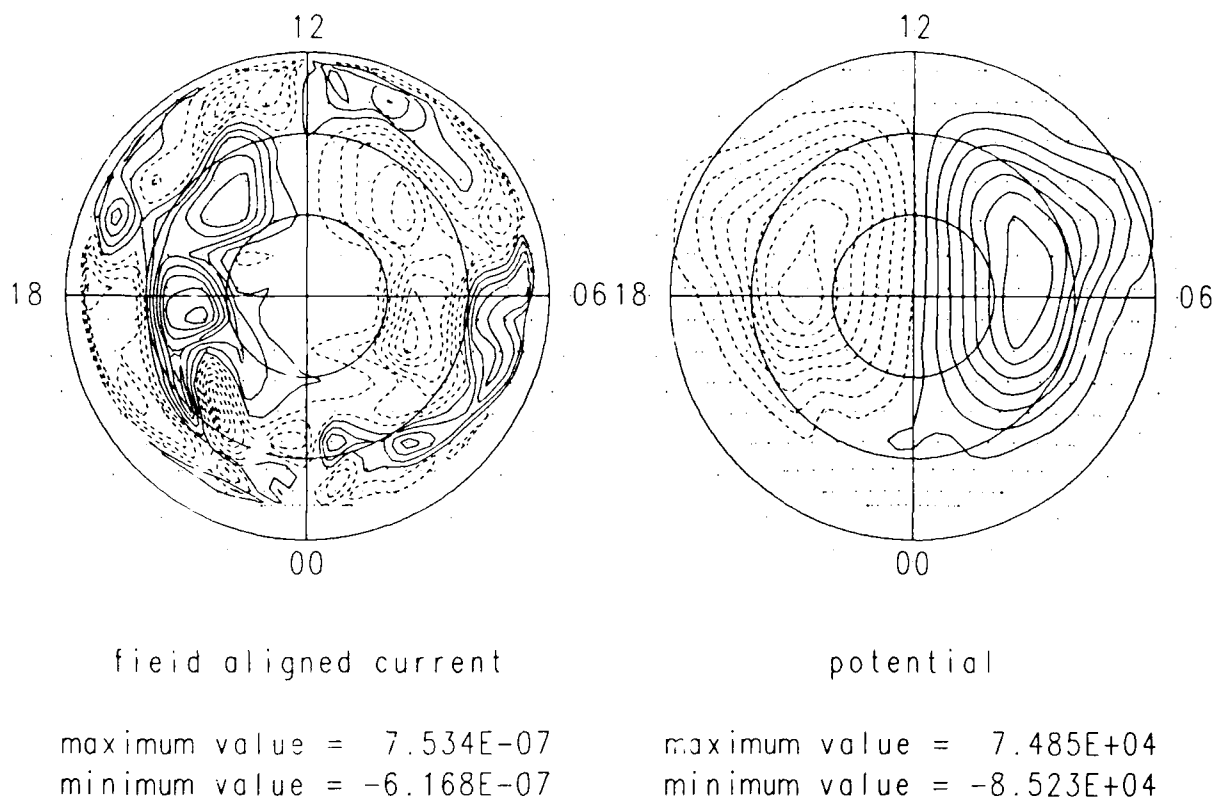
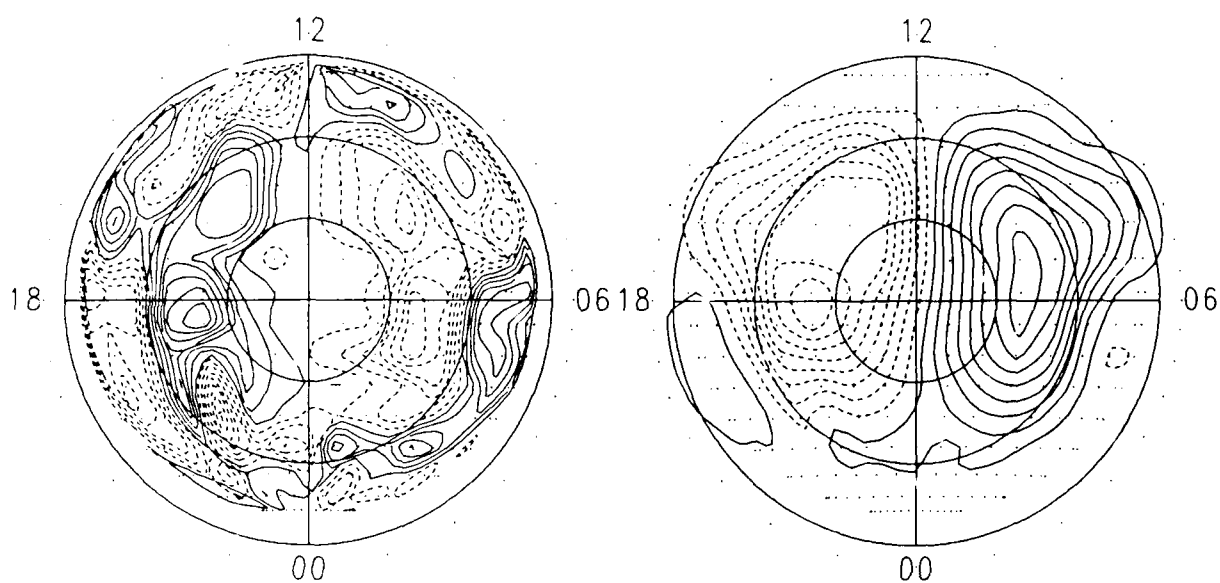


Figure 1: The field-aligned currents (amp/m^2) on the left and electric potential (volts) on the right as a function of magnetic latitude, 60° - 90° , and solar hour angle. For currents, the solid (dashed) contours indicate out of (into) the ionosphere; and for voltage, solid (dashed) contours indicate positive (negative) potential. The contours are for initial conditions for HANE plume simulations. The current contours show the Region 1 system between 70° and 80° magnetic latitude, and the Region 2 currents at lower latitude. The potential contours show the anti-sunward plasma convection above about 75° latitude and sunward convection at lower latitudes. Contours are spaced evenly between the maximum and minimum values indicated.

Northern Hemisphere step=15100 time= 6.015E+03



field aligned current

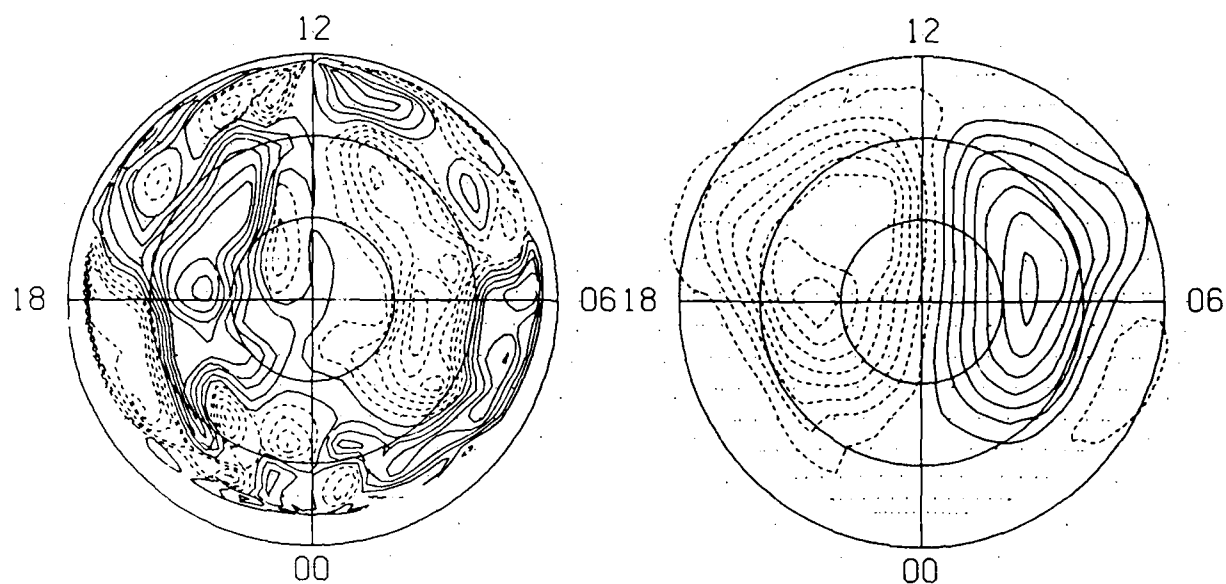
potential

maximum value = $6.774E-07$
minimum value = $-5.619E-07$

maximum value = $6.417E+04$
minimum value = $-6.984E+04$

Figure 2: Same as Figure 1 one minute after introduction of HANE conductivity.

NORTHERN HEMISPHERE STEP=16000 TIME= 6.431E+03



FIELD ALIGNED CURRENT

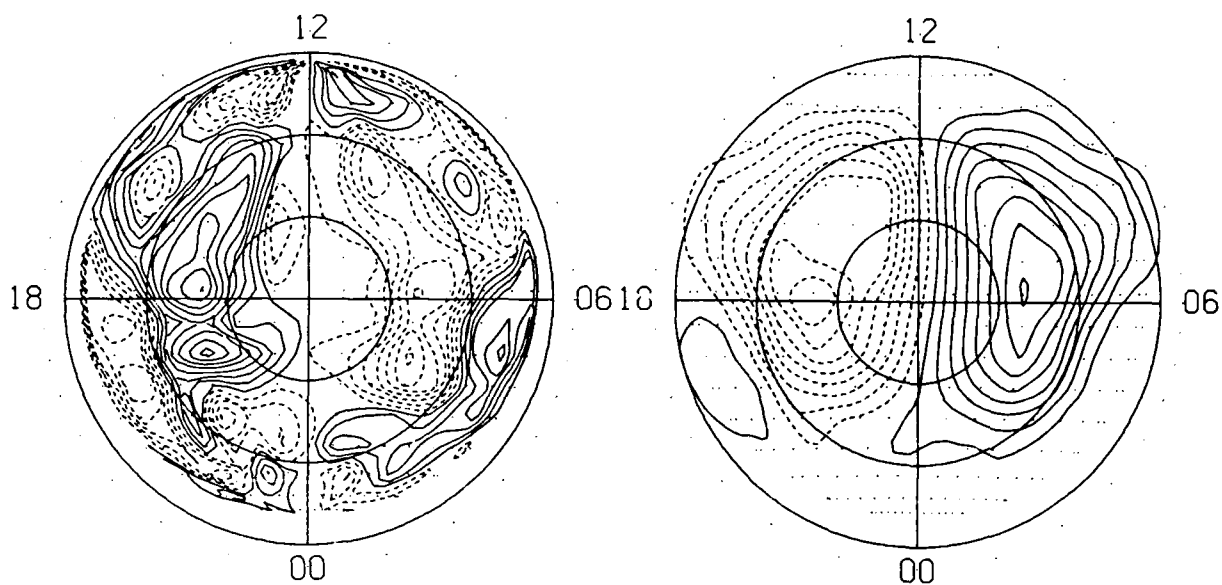
MAXIMUM VALUE = $6.289E-07$
MINIMUM VALUE = $-4.736E-07$

POTENTIAL

MAXIMUM VALUE = $6.544E+04$
MINIMUM VALUE = $-7.317E+04$

Figure 3: Same as Figure 2 but 7 minutes later.

NORTHERN HEMISPHERE STEP=17000 TIME= 6.893E+03



FIELD ALIGNED CURRENT

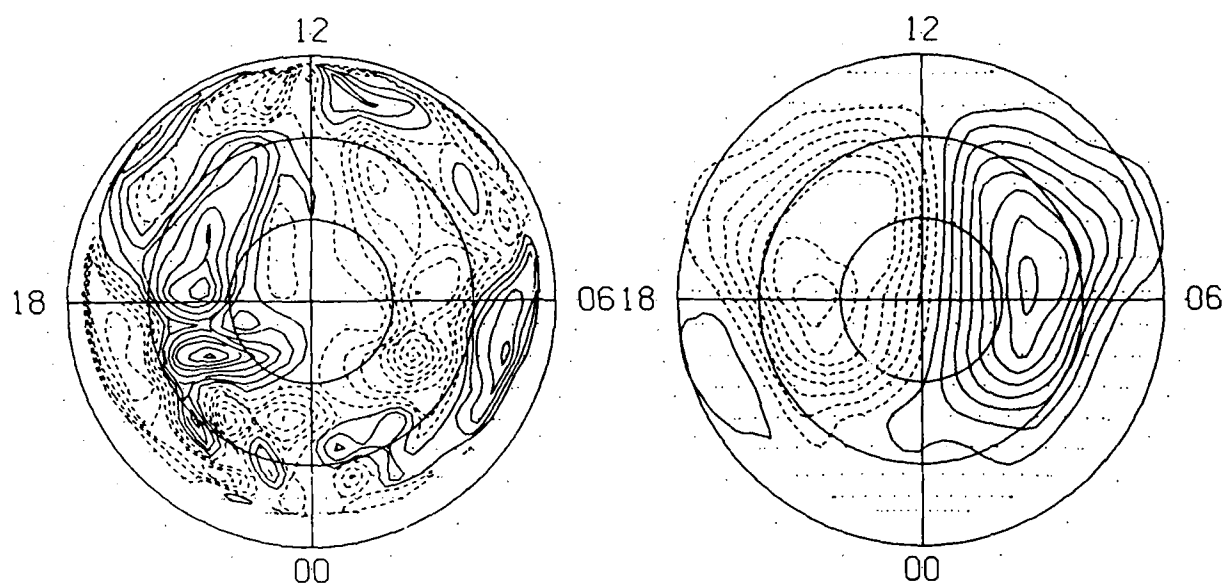
MAXIMUM VALUE = $6.027E-07$
MINIMUM VALUE = $-4.894E-07$

POTENTIAL

MAXIMUM VALUE = $6.032E+04$
MINIMUM VALUE = $-6.889E+04$

Figure 4: Same as Figure 2 but 15 minutes later.

SOUTHERN HEMISPHERE STEP=17000 TIME= 6.893E+03



FIELD ALIGNED CURRENT

POTENTIAL

MAXIMUM VALUE = $6.594\text{E-}07$
MINIMUM VALUE = $-6.656\text{E-}07$

MAXIMUM VALUE = $6.176\text{E+}04$
MINIMUM VALUE = $-6.898\text{E+}04$

Figure 5: Plots for south polar region, same as Figure 4.

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