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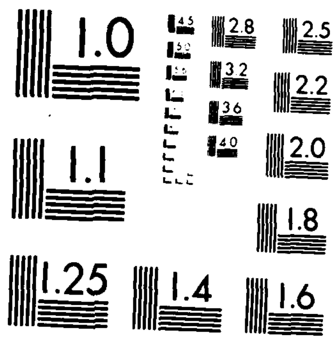

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Region 1 Birkeland Currents from a Global MHD Simulation of the Magnetosphere

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Geophysical and Plasma Dynamics Branch
Plasma Physics Division

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Global numerical MHD simulation data for the earth's magnetosphere has been used to calculate Birkeland current systems in the polar ionosphere. In this report, we show the results for the Region 1 Birkeland currents. We demonstrate how the currents are organized on open or closed field lines in daytime and nighttime sectors. The current source regions are identified and driving mechanisms are discussed.

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CONTENTS

REGION 1 BIRKELAND CURRENTS FROM A GLOBAL MHD SIMULATION OF THE MAGNETOSPHERE

Introduction

The study of large scale geomagnetic field aligned currents, which couple the dynamics of the magnetosphere and the high latitude ionosphere, has been an area of intense research interest in recent years. These currents, first postulated by Birkeland [1908] to be responsible for geomagnetic activity and auroral phenomena in the polar regions, were first observed, by Arnoldy [1974], Zmuda and Armstrong [1974a,b], and Sugiura [1975] and have now been extensively measured and documented by satellite and rocket magnetometers. Much of the recent experimental research has been reviewed by Potemra [1979], Potemra et al. [1979], Burch and Heelis [1978], Saflekos et al. [1982], Greenwald [1982], Burke [1982], and Potemra [1982].

The large scale Birkeland currents are observed in two rings which encircle the polar regions. The poleward ring has been called the "Region 1" system and the equatorward ring the "Region 2" system, [Iijima and Potemra, 1976a,b]. The Region 1 currents are earthward in the morning sector and away from the earth in the evening sector, while the Region 2 currents are in the opposite direction in each sector. The Region 1 currents have been identified as magnetospheric driving currents and are directly associated with the solar wind-magnetospheric dynamo, whereas the Region 2 currents are considered to be response currents [Schield et al., 1969; Wolf, 1974]. The Region 1 and Region 2 Birkeland current systems and their sources and sinks are a fundamental link in the solar wind-magnetosphere-ionosphere interaction and dynamics.

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Quantitative theoretical and simulation studies of Birkeland current systems and magnetospheric dynamics were begun by Wolf and Harel [1979] and Harel et al. [1979]. This pioneering work and continuing research [Harel et al., 1981a; Harel et al., 1981b; Spiro et al., 1981; Wolf et al., 1982; Chen et al., 1982; and Karty et al., 1982] has led to a major advance in understanding Birkeland currents and their role in magnetospheric dynamics. These simulation studies have treated the inner magnetosphere-ionosphere system in detail and therefore have provided a quantitative model for the Region 2 currents which are consistent with observations. However, the Region 1 currents are outside or on the boundary of the simulated region of the magnetosphere and are therefore untreated.

In this brief report we present preliminary simulation results for the Region 1 Birkeland current systems. The results are extracted from a global MHD solar wind magnetosphere simulation and therefore provide a description of the driving current system. Owing to limited numerical resolution and an inadequate treatment of the ionosphere, the currents are not quantitatively accurate. However, we are able to identify those regions of the magnetosphere which act as a dynamo. Moreover, we are able to at least partially identify the driving mechanisms.

Method

The Birkeland currents were derived from the three-dimensional MHD global magnetosphere simulation model [Brecht et al., 1982]. The simulation is on a cartesian mesh with a resolution of two earth radii near the earth. The currents are computed on a cubic mesh centered on the earth with the faces of the cube located at about five earth radii geocentric altitude as shown in Figure 1. There are 36 mesh points on each face of the cube so that 76 mesh points map into each of the north and the south polar regions. All but four of these mesh points map along dipole field lines into the latitude range between 65 and 77 degrees.

At each mesh point on the surface of the cube we calculate $J_{\parallel}/|B| = (\nabla \times \underline{B})\cdot\underline{B}/\underline{B}\cdot\underline{B}$ from the magnetic field intensity $\underline{B}$ in the simulation results. We assume that within the cube, the flow is given by the electrostatic approximation with infinite field-aligned conductivity. Then the quantity $J_{\parallel}/|B|$ is a constant along flux tubes and can therefore be easily mapped to ionospheric altitudes along the assumed dipole field lines. This simplifying assumption is probably reasonable during most quasi steady flow conditions. The magnitude of the current density in the ionosphere is then obtained by multiplying $J_{\parallel}/|B|$ by the ionospheric magnetic field intensity, 6×10^{-5} T. Since this calculation is performed after the fact, there is no ionospheric feedback on the computed magnetosphere.

For the results shown here the solar wind density was 5 cm^{-3} and the velocity was 400 km sec^{-1}. The interplanetary magnetic field was 5 nT southward. The magnetosphere configuration was open with merging between the IMF and the geomagnetic field occurring on the bow of the magnetosphere. Rapid merging was not occurring in the magnetotail since the data shown was selected during a quiet time between two discrete reconnection and acceleration events in the tail.

We also compute an example of the plasma convection pattern in the polar ionosphere. The electric potential is derived by solution of $\nabla\cdot(\Sigma\nabla\psi) = J_{\parallel}$, where ψ is the electric potential and Σ the conductivity, was chosen to be a uniform scalar 5 mhos, a value which is appropriate to the auroral regions but too large in most of the polar cap.

Results

Figure 2 shows the parallel current in the ionosphere poleward of 60 degrees latitude. A clear Region 1 Birkeland current pattern is apparent. The solid contour lines show the upward current in the afternoon-evening sector of the polar region, while the dashed contours show the downward current on the morning side. No clear Region 2 current system can be seen primarily owing to the absence of data points below 65° latitude. The mid-day currents occur primarily at latitudes above 75°, while at dawn, at dusk, and at night the currents are at 68° to 72° latitude. The daytime currents are concentrated near 0900 and 1500 hours, the evening currents between 1700 and 2300, and the morning currents between 0000 and 0700. Current density magnitudes range generally between 0.1 and 0.2 x 10^{-6} amp m^{-2}.

Figure 3 shows the polar plasma convection consistent with the calculated currents. The convection potential was calculated using a uniform ionospheric conductivity of 5 mho; there were no auroral conductivity enhancements. The total cross polar cap potential is 15 kV. The convection pattern shows the typical anti-solar convection poleward of the Region 1 current system and sunward flow at lower latitudes.

In order to determine the source regions for the Region 1 current in the simulation results, we have traced magnetic field lines from the polar ionosphere into the magnetosphere and solar wind. The field line tracing results show a clear delineation between open and closed geomagnetic field. The boundary between open and a closed field lines is shown in Figure 4 plotted over the current system of Figure 2.

The results of field line tracing in Figure 4 show three distinct source regions for the Region 1 Birkeland currents. The dayside currents, between 0800 and 1600 hours, close to the bow magnetopause and to the polar magnetopause on open polar field lines. The dawn currents, between 0400 and 0700, and dusk currents between 1700 and 2000, close to a boundary layer in the equatorial plane on the flanks of the magnetosphere and are on closed field lines. The nightside currents, between 2000 and 0400, close along the boundary between the plasma sheet and the tail lobes and are on open field lines. The characterization of an individual field line as open or closed is not always perfect owing to limited resolution in the simulation and to numerical error in the field line tracing. However, after careful study of a number of different cases we believe that the characterization provided above is accurate.

Discussion and Conclusions

In this discussion we would like to address a number of concerns and points of interest. It appears that the Region 1 Birkeland current density is about one order of magnitude too small compared to observed values [Iijima and Potemra, 1978], whereas the integrated current densities are about a factor of 5 too small. The differences could arise from a number of causes. As mentioned previously, the numerical resolution (> 2 R_e between grid points) is not nearly fine enough to see narrow structures in the magnetosphere. The low resolution has two effects; the currents tend to be spread over a broader area, and the peak magnitude of the current is reduced. Unfortunately, in the absence of higher resolution calculations it is difficult to assess the impact of resolution on these results.

Another cause of the reduced Birkeland current magnitudes is related to the current closure mechanism at low altitudes. The ionosphere acts as a load on plasma dynamics in the magnetosphere. As the ionospheric conductivity is increased (decreased) the load on the magnetosphere is increased (decreased) and the driven Birkeland currents increase (decrease) in magnitude. The magnetosphere-ionosphere currents are regulated by a balance between the strength of the dynamo and the size of the load. In the simulation, since the ionosphere was not a prescribed boundary condition, we cannot assess the size of the load and therefore cannot assess the Birkeland current magnitude relative to observations. In the simulation the Birkeland currents close at low altitude via a loss of resolution; the current carrying flux tubes cannot be distinguished between widely spread grid points. Whether this closure of currents in some sense resembles the ionosphere conductivity is difficult to know. However, current closure due to loss of numerical resolutions is a dissipative process. As such, it serves as a load on the dynamo and in that sense should act similarly to the real ionosphere.

The magnitude of the convective potential across the polar cap of 15 kV is also smaller than the average observed potential of about 40 kV and should probably be higher for a 5 gamma southward IMF [Stern, 1979]. This difference i probably due to both the smaller values of the sheet current densities and the simplified model for the ionospheric conductivity used to generate the convection pattern. The ionospheric electric fields are not fully consistent with the magnetospheric simulation since they are calculated after the fact and are not a part of the simulation. Nevertheless, both the simulation Birkeland currents and convection potentials bear a strong resemblance to those actually observed.

We now turn our attention to the current source regions. The boundary between open and closed geomagnetic field lines clearly divides the Region 1 currents into three distinct systems. At dawn and at dusk the currents flow on closed field lines, while during the day and at night the currents flow either along the boundary or on open field lines. These systems will now be discussed individually in greater detail.

The geomagnetic field lines which carry the dawn and dusk currents are highly distorted in the anti-solar direction. Field lines poleward of the current sheet and penetrating the ionosphere at 0700 and 1700 hours cross the equatorial plane about 2 earth radii in the anti-solar direction while those near 0400 and 2000 hours extend more than 40 earth radii tailward. Field lines equatorward of the sheet are substantially less distorted. All these current carrying field lines cross the equatorial plane in a boundary layer near the magnetopause. The reader might expect that a low latitude boundary layer current would extend further toward mid-day than 0700 and 1400 hours. In reality they probably do and the termination in the simulation results is associated with numerical resolution problems along the dayside magnetopause.

The current systems on closed field lines are driven by a momentum coupling process from the magnetosheath, across the magnetopause, and into a low latitude magnetosphere boundary layer. In the simulation code this coupling is due to both numerical viscosity and an artificial viscosity in the momentum equation [Brecht et al., 1982]. At the present, however, we are unable to make a quantitative comparison between the simulation viscosity and an actual physical viscosity in the magnetosphere. The effective viscosity in the simulation is likely to be substantially larger than the viscosity which actually pertains to the low latitude boundary layer. We intend to address this question in a more quantitative manner in the future.

The dayside and nightside currents have a different driving mechanism. It is tempting to associate the currents on open field lines to a process which is driven by magnetic merging. This appears not to be the case. During the simulations we have observed sporadic rapid merging and acceleration of plasma in the magnetotail. The merging and acceleration processes occur with virtually no disturbance of the Region 1 current systems. We therefore conclude that the current systems presented here are not associated with magnetic merging processes.

The dayside Birkeland currents on open field lines appear to cross the nose magnetopause and extract momentum from the anti-solar magnetosheath flow. By loading the currents in the magnetosheath which reaccelerate plasmas away from the bow stagnation point the Birkeland currents and the ionosphere draw energy directly from the solar wind. These dayside open field line currents appear to occur in the same region as the cusp currents of Iijima and Potemra [1976b] and D'Angelo [1980]. Unfortunately, the simulation currents have opposite polarity to the cusp systems which were observed. We are unable to explain this discrepancy.

The simulation nightside currents occur in the same region as those observed in the magnetosphere [Aubrey et al., 1972; Fairfield, 1973; Sugiura, 1975; Frank et al., 1981; Kelley et al., 1981]. The mechanism responsible for driving these nightside currents has not been identified at this time. The analysis of the source region is very difficult owing to the weak fields, low plasma densities, apparently unorganized flow, and low numerical resolution in this region of the simulation. It is possible that the mechanism of Rostoker and Bostrom [1976] may be responsible for these currents but at present we cannot be sure. Study is continuing to identify the source of these currents.

In conclusion, we would like to summarize the results. Numerical MHD simulations of the magnetosphere produce Birkeland current systems which are in reasonable agreement with observations. Here we have presented results for the Region 1 currents. These currents are divided by the open-closed field line boundary into three separate sytems; a low latitude boundary layer system along the flanks of the magnetosphere, a dayside open field line system which has its source in the magnetosheath, and a nightside open field line system on the boundary between the tail lobes and the plasma sheet. We have also discussed possible source mechanisms responsible for these systems.

The results presented here are preliminary. Improvements are being made in the simulation codes with regard to resolution and in order to simulate a realistic ionosphere boundary condition. A factor of two resolutions has been obtained by refinement of the numerical mesh, and an additional factor of two has been achieved by upgrading the computational algorithms. The new ionospheric boundary conditions allow ionospheric fields and flows to feed back on the magnetospheric dynamics. We expect that the continued work will lead to improved results in the near future.

Acknowledgments

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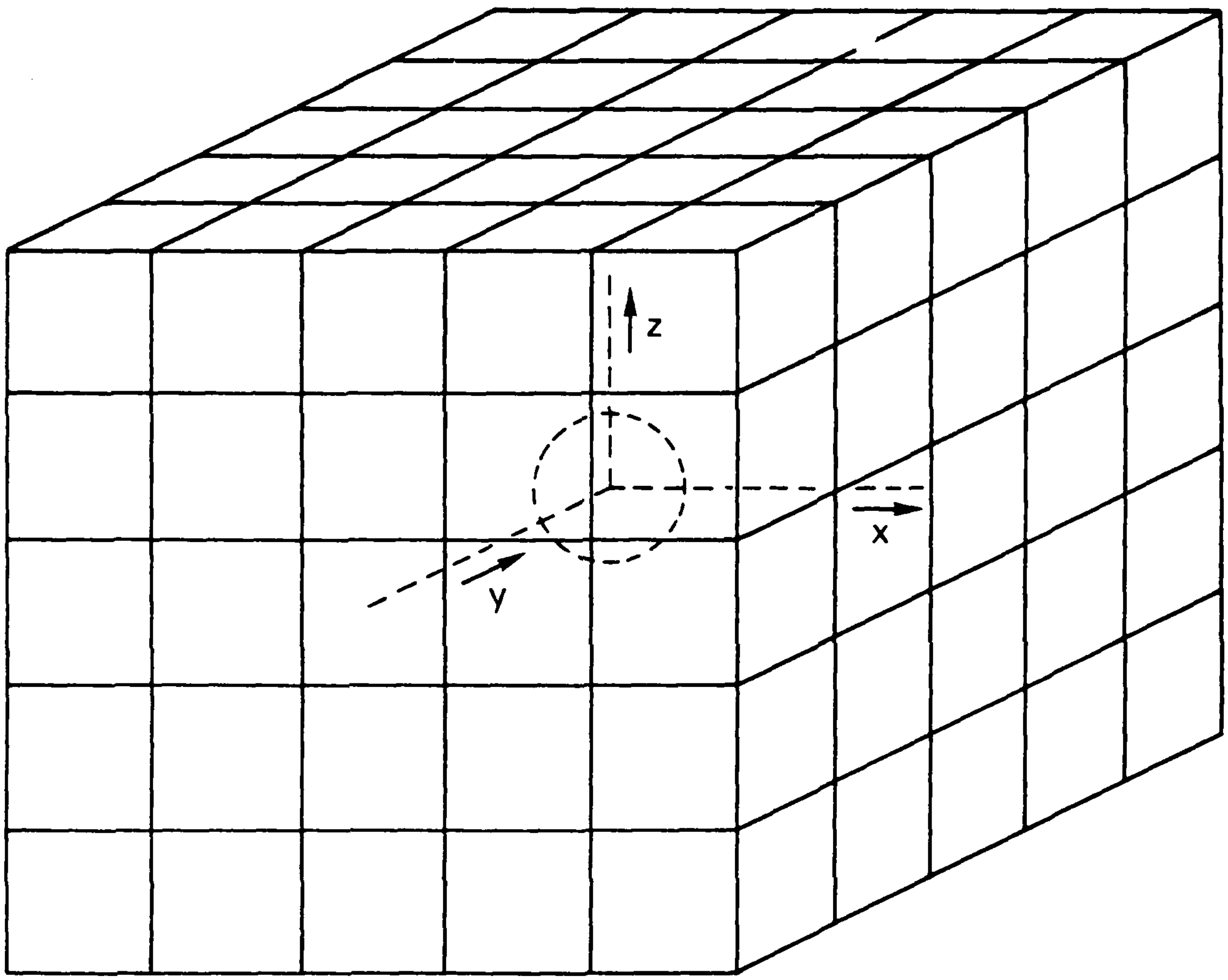

Figure 1. A diagram of the cubic mesh used to calculate parallel currents from the global simulation results. The earth is located at the center and each face of the cube is about 5 earth radii from the earth. The currents are mapped from the mesh points on the cube along dipolar field lines to the polar ionosphere.

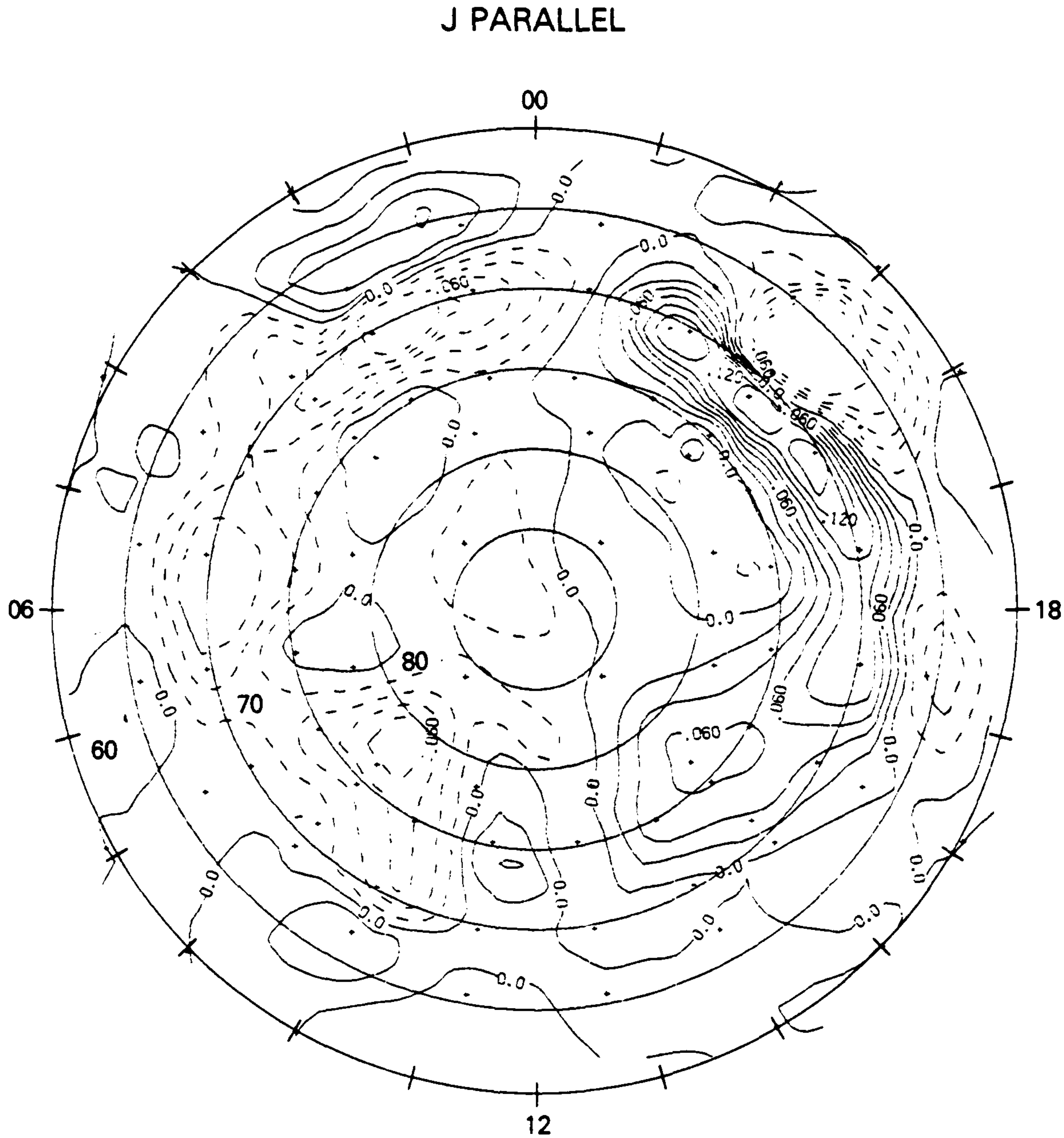

Figure 2. Contours of parallel current density in the polar region at the ionosphere. The solid/dashed contours show currents out of/into the polar ionosphere. The nested solid contours on the right show the evening System 1 Birkeland currents, while the nested dashed contours on the left show the morning currents. Units for the current density are 10^{-6} amp m^{-2}.

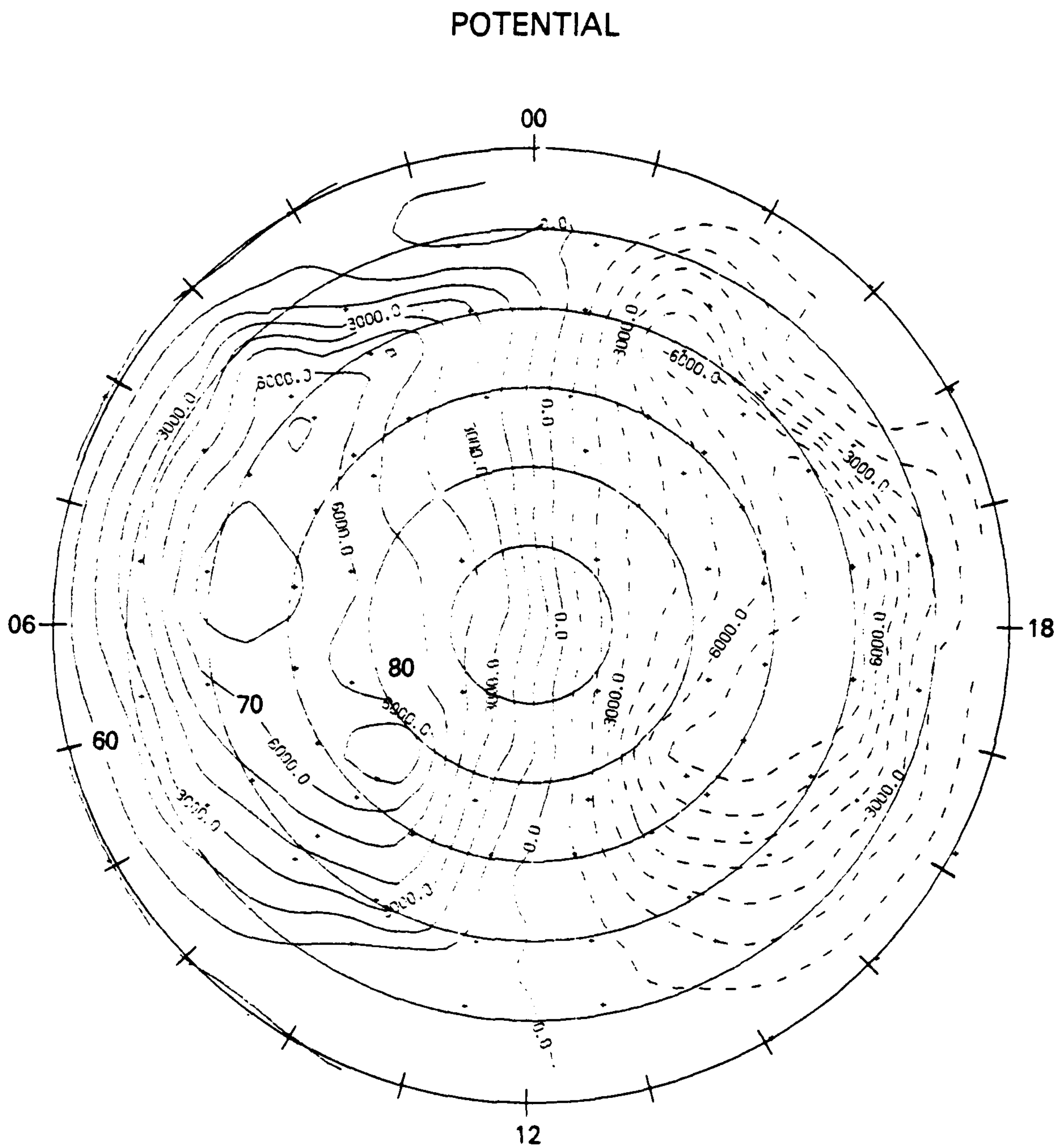

Figure 3. Equipotential contours in the polar ionosphere. The potential shows a typical two cell convection pattern with anti-sunward flow over the polar cap and sunward flow at lower latitudes. The potential is in volts. Solid/dashed contours are positive/negative.

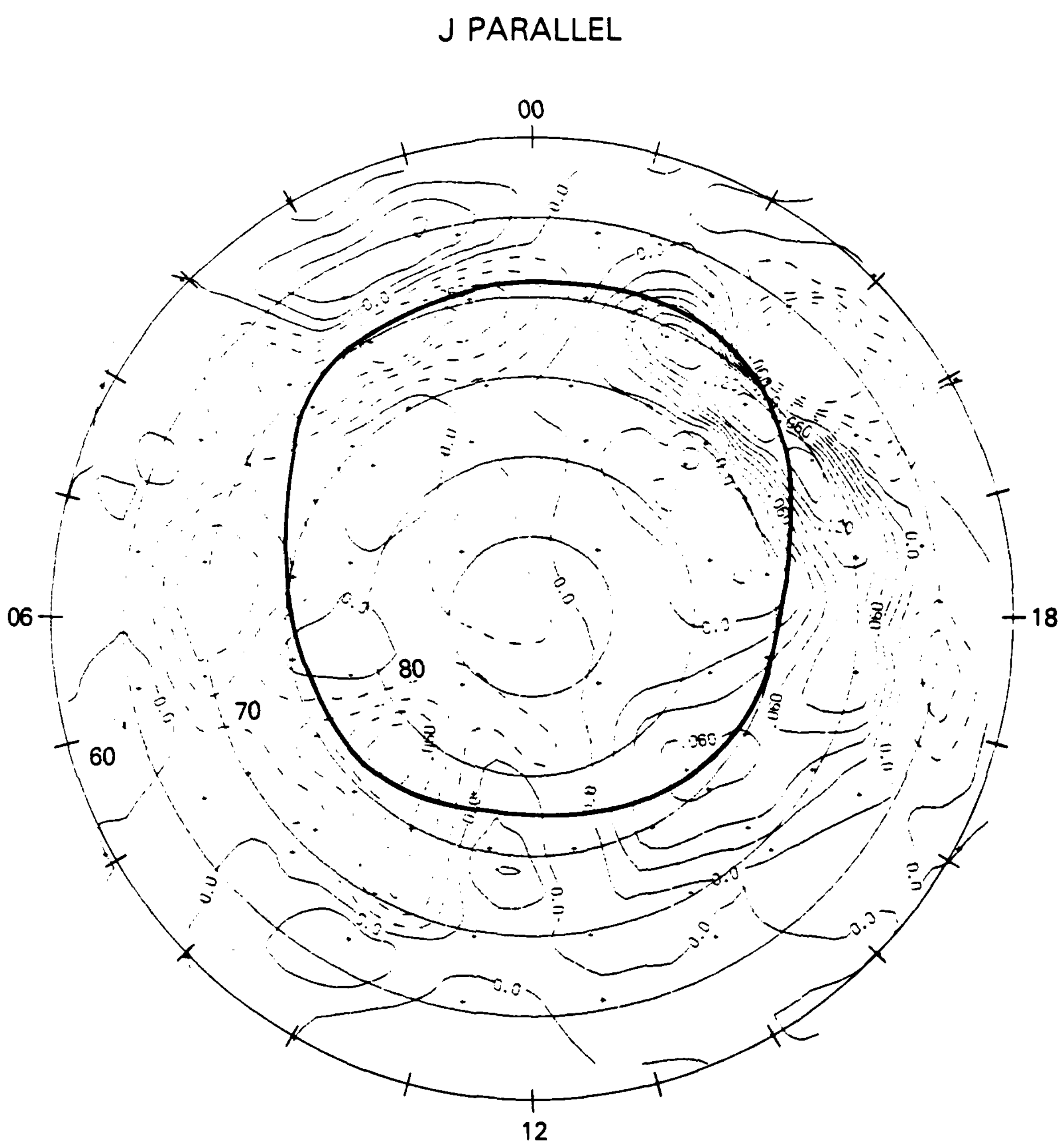

Figure 4. A replot of Figure 2 but with the boundary between open and closed geomagnetic field lines superimposed. The open/closed field lines are at higher/lower latitudes. The Birkeland currents are clearly divided into three distinct regions. The currents near dawn and dusk are on closed geomagnetic field lines, while those during day and night are on the boundary or on open field lines.

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