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Plasma Convection in the High-Latitude *F*-Region

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Introduction

The convective motion of the *F*-region plasma at high latitudes is one of the most important parameters affecting its distribution and composition. Above invariant latitudes of about 60°, the dominant driving force for this convection is an electric field that originates outside the ionosphere. The electric field is produced in the magnetosphere, or at its boundary with the interplanetary medium, by an interaction between the geomagnetic field and the solar wind. The electric field is communicated to the ionosphere along the Earth's highly conducting magnetic field lines. Thus, our understanding of the high-latitude *F*-region plasma motion is not only necessary for a satisfactory description of the *F*-region itself, but can also contribute significantly to our understanding. of the interaction of the Earth's atmosphere with the interplanetary medium The existence of very different convection patterns is pointed out here, and their implications for *F*-region plasma distributions and for the interaction of the magnetosphere with the solar wind are discussed.

Observations

Measurements of the high-latitude ionospheric electric field have been made for several years on satellites [1] and balloons [2] using dipole antennas. Details of the electric field configuration on relatively small spatial scales are obtained from optical tracking of barium ion clouds [3]. More recently two and three dimensional *in situ* measurements of the *F*-region ion velocity have given more information on the nature of the global ionospheric motion [4, 5]. These measurements all agree that the dominant motion of the plasma above invariant latitudes of about 60° is one of two-cell-convection perpendicular to the magnetic field. Above invariant latitudes of 70° to 75° the plasma motion is generally directed away from the Sun with return flow toward the Sun at lower latitudes. The ion velocity is quite variable but is of the order of 1 km s^{-1} on the dayside and

500 m s^{-1} on the nightside. In the regions near dawn and dusk the boundary between sunward and antisunward convection may be well defined and has been termed "polar cap boundary" (the polar cap being the region of antisunward convection). While other definitions of the polar cap exist, this definition

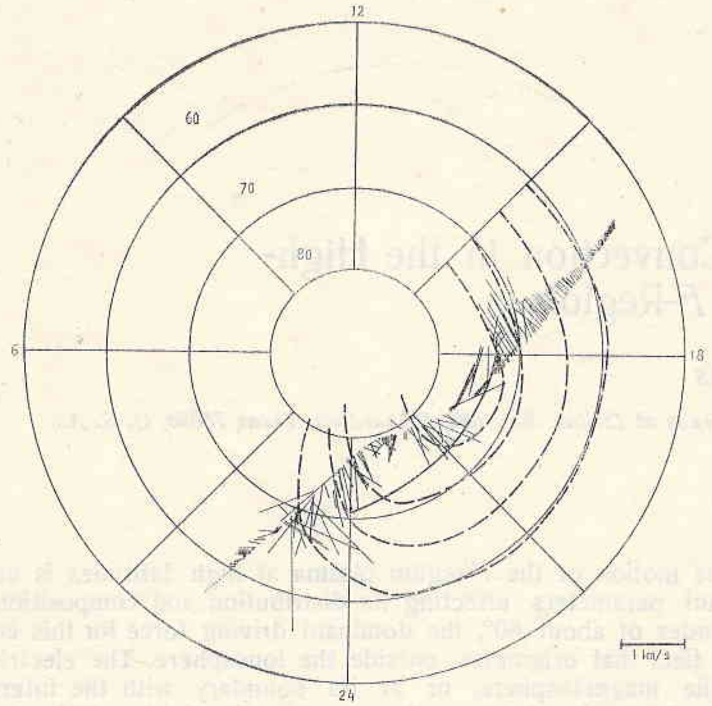

Fig. 1. Horizontal ion drift velocity vectors from AE-C orbit 13269. The dashed lines represent most probable convection trajectories drawn by eye. The heavy solid line is the location of the polar cap boundary which is assumed to be coincident with the poleward edge of the auroral zone

AE-C ; Ion drift velocities ; Day 76164 ; Orbit 13269 : Southern hemisphere
INVLAT V MLT

is used throughout this work. Near noon and midnight the flow changes from sunward to antisunward and vice versa, and the definition of the polar cap becomes less precise. Quite sophisticated theoretical models have been developed [6] to show that these generally observed features of the ionospheric convection pattern are consistent with an electric potential difference of between 50 and 100 kV applied across the magnetosphere. Simple convection models, assuming such a potential drop across the polar cap and assuming a centered magnetic dipole field with electric equipotential field lines, have been adopted for studying the *F*-region plasma distribution [7, 8]. Such studies have proved very illuminating and have made a positive step toward explaining some features of the high-latitude ionosphere. However, many features remain unexplained due to some severe restrictions imposed by the convection model. The most severe of these are probably that the convection inside the polar cap is directly antisunward and that the polar cap appears as a circle centered at the geomagnetic (geographic) pole.

Fig. 1 shows the horizontal ion drift velocity observed by the RPA/Drift Meter on the Atmosphere Explorer-C satellite [9, 10]. The data from the southern hemisphere pass of orbit 13269 are shown on an invariant latitude (Λ) and magnetic local time (MLT) dial which is in a coordinate system co-rotating with the Earth. The lines extending from the spacecraft track are indicative of the direction and magnitude of the instantaneous ion velocity. The

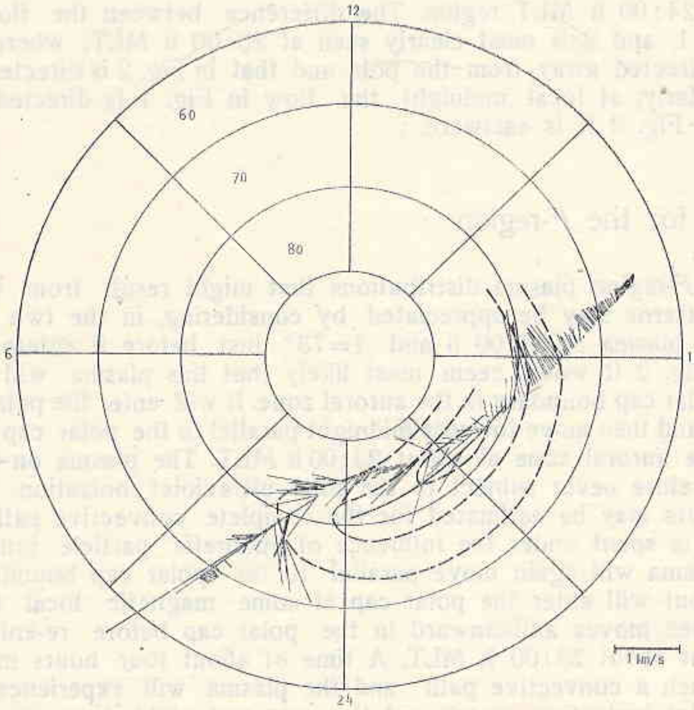

Fig. 2. Horizontal ion drift velocity vectors from AE-C orbit 13254; See Fig. 1 for details

AE-C; Ion drift velocities; Day 76163; Orbit 13254; Southern hemisphere INVLAT V MLT

scale is shown at the bottom right of Fig. 1. The dashed lines represent the most reasonable convective trajectories and have been drawn by eye with some attempt to conserve horizontal magnetic flux. While the data reveal one convective cell, it is not unreasonable to expect a second cell on the morning-side. The data are therefore consistent with the expected flow pattern. However, at about $\Lambda = 75°$ and 20:00 h MLT the flow inside the polar cap is not directed exactly antisunward, but rather it is directed away from the pole with a small component parallel to the noon-midnight plane and directed towards midnight. The arrow marks the boundary between flow components that are sunward and antisunward. It should also be noted that the noon-midnight meridian does not mark a line of symmetry in the convection pattern. This may be due to lack of symmetry altogether or to the fact that the line of symmetry has been rotated towards later local times.

Figure 2 shows the horizontal ion velocity vector observed by AE-C on the southern hemisphere pass of orbit 13254. While the location in invariant latitude and magnetic time is very similar to that shown in Fig. 1, the convective signature represented by the dashed lines is very different. The variability of the observed ion velocity in the 20:00 to 21:00 h MLT sector is due to the passage of the satellite along the poleward edge of the auroral zone. This boundary is shown by the heavy solid line in Figs. 1 and 2, and is also representative of the polar cap boundary. These data are a dramatic example of flow in the polar cap which is not antisunward but eastward in most of the 18:00 to 24:00 h MLT region. The difference between the flow geometries in Figs. 1 and 2 is most clearly seen at 20:00 h MLT, where the flow in Fig. 1 is directed away from the pole and that in Fig. 2 is directed towards the pole. Similarly, at local midnight the flow in Fig. 1 is directed antisunward while in Fig. 2 it is eastward.

Implications for the F-region

The different F-region plasma distributions that might result from these two convection patterns may be appreciated by considering, in the two cases, the history of the plasma at 23:00 h and $\Lambda=73°$ just before it enters the auroral zone. In Fig. 2 it would seem most likely that this plasma will move parallel to the polar cap boundary in the auroral zone. It will enter the polar cap near 19:00 h MLT and then move towards midnight parallel to the polar cap boundary. It re-enters the auroral zone at about 23:00 h MLT. The plasma on such a trajectory is therefore never subject to the solar ultraviolet ionization. A time of about two hours may be estimated for the complete convective path, at least half of which is spent under the influence of energetic particle ionization. In Fig. 1 the plasma will again move parallel to the polar cap boundary in the auroral zone but will enter the polar cap at some magnetic local time near 09:00 h. It then moves antisunward in the polar cap before re-entering the auroral zone at about 23:00 h MLT. A time of about four hours may be estimated for such a convective path and the plasma will experience both the solar ultra-violet ionization source and the casp and night time auroral zone particle sources. It should not be surprising that under identical auroral zone conditions over an order of magnitude, difference in observed total ion concentration may be expected at 23:00 h MLT just before the plasma enters the auroral zone. It has been assumed here that the ion velocity in the polar cap is uniform. There are even greater consequences to the F-region plasma distribution if the convection pattern of Fig. 2 represents a redistribution of the polar cap electric potential so that the plasma flows rapidly parallel to the polar cap boundary at the expense of very slow plasma flow in the middle of the polar cap. Then the plasma in Fig. 1 that convects through the dayside casp may reach $\Lambda=80°$ at midnight about 1 h later. However, the same plasma flowing according to Fig. 2 may take many hours to reach the same location, leading to total ion concentrations that may differ by 2 or 3 orders of magnitude. Only the effect of the plasma convection on plasma in the polar cap has been discussed here. However, very subtle changes to the convection pattern can have dramatic consequences for the plasma distribution in the region of $\Lambda=60°$. The symmetric centered convection model used in [7] and [8] predicts the existence of a flow stagnation point at 18:00 h MLT and about $\Lambda=63°$. Unfortunately, such a location for the stagnation point cannot successfully explain the observed characteristics of the mid-latitude F-region trough. However, it has been shown [11] that a convection pattern similar to that in

Fig. 2 can move the stagnation point to magnetic local times as late as 23:00 h. Under these conditions theoretical models are in a position to reproduce many of the mid-latitude trough characteristics.

Implications for the Magnetosphere

The existence of field aligned currents and large field aligned potential differences [12, 13] makes the assumption that electric equipotential magnetic field lines extend from the ionosphere to the magnetosphere extremely dangerous. It would also suggest that the mapping of observed *F*-region electric potential distributions into the magnetosphere is of dubious value. However, if it is assumed that the flow configuration near the *F*-region polar cap boundary is at least qualitatively similar to the flow near the corresponding boundary in the magnetosphere, then the *F*-region observations may become extremely useful. Whether this corresponding boundary lies at the magnetopause or inside the magnetosphere depends on the nature of the interaction of the magnetosphere with the solar wind. The flow configuration of Fig. 1 suggests that there is a substantial flow across the polar cap boundary throughout the nightside. This may imply that in an open magnetosphere a region of reconnection extends across a substantial portion of the magnetotail. Alternatively, it may indicate that the "viscous interaction" associated with a close magnetosphere gradually weakens as the plasma moves down the tail. Figure 2 would suggest that in an open magnetosphere a region of reconnection in the tail occupies only a small region near local midnight and that all the antisunward convecting plasma converges towards this point under the influence of the solar wind electric field. Alternatively it may suggest that the degree of "viscous interaction" in a closed magnetosphere is very strong and that the boundary layer flow extends well down the tail. It should be pointed out that the existence of a boundary layer flow and an open magnetosphere are not mutually exclusive. The situations described here represent the classical extremes of open and closed magnetospheres.

A quantitative description of the *F*-region plasma distribution depends not only on the convective motion of the plasma but also on the details of the different sources and sinks of ionization that are encountered during the convective motion. It is therefore important to establish the relationship between particle precipitation zones and plasma convection patterns. While it has been shown that very different convection signatures can be observed, there is no evidence offered for the stability of these patterns on time scales of the few hours required for their completion. It may be confidently expected that the convection patterns depend on substorm activity and other solar and interplanetary magnetic parameters which change on time scales of 1 hour.

The construction of a model convection pattern which may represent the observed flow characteristics under given solar and magnetic conditions is of great importance to successful modelling of the high latitude *F*-region.

The understanding of high-latitude *F*-region convection will not shed light directly on the nature of the interaction between the magnetosphere and the solar wind. However, the behaviour of this convection and its relationship to the field aligned current distribution and energetic particle precipitation zones may help to assess the relevance of such data to magnetospheric processes. In particular, the behaviour of the *F*-region plasma flow near the polar cap boundary as a function of substorm activity and changes in other solar and magnetic parameters may well be indicative of the variability of the magnetosphere-solar wind interaction. The needed *in situ* measurements of the magnetosphere and solar wind are, or soon will be, undertaken. Simultaneous measurements of electric fields, plasma motion, field aligned currents and energetic particles in the ionosphere will be undertaken by the Dynamics Explorer Satellites and by Intercosmos satellite payloads. The data from these satellites will prove valuable to the advance in understanding of the dynamics of the high-latitude ionosphere.

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Конвекция плазмы в высокоширотной *F*-области

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(Резюме)

Измерения скорости ионов в высокоширотной F-области показывают, что конвекция может иметь довольно разную конфигурацию. При изменении конфигурации конвекции можно ожидать в данном месте разницы в ионной концентрации на несколько порядков. Эти изменения, вероятно, являются результатом разной степени взаимодействия между магнитосферой и солнечным ветром.