NASA-CR-170,377

AEROSPACE REPORT NO
ATR-83(7951)-1

NASA-CR-170377
19830018062

Eddy Intrusion of Hot Plasma into the Polar Cap and Formation of Polar-Cap Arcs

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30 May 1983

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Headquarters, Washington, D.C 20545

Contract No. NASW-3434

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Aerospace Report No.
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ABSTRACT

Under the simple postulate that multiple large-scale detachable magnetospheric convection eddies can exist in the vicinity of the convection reversal boundary and in the polar cap, by Kelvin-Helmholtz instability or otherwise, we show that a number of seemingly disconnected plasma and electric field observations in the polar cap can be organized into a theory of magnetosheath and plasmasheet plasma intrusion into the polar cap. Current theory of inverted-V structures then predicts existence of similar, but weaker, structures at the eddy convection reversal boundaries in the polar cap. A possible consequence is that the polar cap auroras are natural off-shoots from discrete oval arcs and evidently are formed by similar processes. The two arc systems can occasionally produce an optical image in the form of the Θ aurora.

ACKNOWLEDGMENT

It is a pleasure to thank Drs. J. M. Cornwall, R. R. Hoffman, J. F. Fennell, P. F. Mizera, M. Schulz, and R. R. Torbert for helpful conversations.

CONTENTS

FIGURE

I. INTRODUCTION

While a great deal of research has been focused upon understanding the formation of the discrete auroral arc in the oval, relatively little analytical work has been devoted to auroras in the polar cap. Probably because of their relatively inaccessible location, polar-cap arcs have more or less been regarded as a sort of esoteric curiosity.

In this paper we suggest, through a combination of data and theory, that the polar-cap arc is a very important phenomenon indicative of the entry of hot magnetosheath and plasmasheet plasma into the polar cap; thus, our interpretations of plasma and electric field data in the polar cap may have some impact on current notions of plasma processes in the magnetospheric boundary layer.

In Section II of this paper we present plasma and electric field data obtained over the polar cap by the S3-3 satellite. In Section III the central idea of convection eddy intrusion into the polar cap is introduced to organize the main points of the S3-3 observations. In Section IV we return to the convection hypothesis and discuss further relevant points of the hypothesis in the context of other satellite observations.

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II. OBSERVATIONS

Auroral arcs, sometimes aligned in the sunward direction, have been observed well poleward of the auroral oval both optically (e.g., Larsen and Danielson, 1978) and indirectly by energetic charged-particle detectors (see Meng, 1978 and references therein). Reversals in the anti-sunward $\vec{E} \times \vec{B}$ plasma convection have also been observed over the polar cap (Torbert et al., 1981) and have been attributed to irregular polar convection patterns. Based on magnetic observations, Horwitz and Akasofu [1979] have also discussed the possibility of multi-cell convection patterns during northward IMF. In this paper we discuss one example of energetic charged-particle data and $\vec{E} \times \vec{B}$ plasma convection observations from a dawn-dusk polar cap crossing of the S3-3 spacecraft between 6000 and 8000 kilometers altitude, and show that both the energetic plasma and convecton data are well organized by a simple model of eddy intrusion of boundary layer plasma into the polar cap.

The lower left panel of Figure 1 shows $\vec{E} \times \vec{B}$ plasma convection data (Day 246, 1976 from Torbert et al., 1981) measured along the S3-3 path over the polar cap. Noon is toward the top of the figure, and dawn to the right. Although only the flow component perpendicular to the satellite path is plotted, it is easy to infer the sunward/anti-sunward flow components because of the dawn-dusk orientation of the satellite orbit.

A fairly simple convection pattern is observed in the dawn sector, with a sharp transition from sunward to anti-sunward flow occurring at 75.4° invariant latitude. The convection pattern in the dusk sector is much more complicated, with four flow transitions occurring above 70° invariant latitude (labeled I, II, III, IV on the figure). The upper panel of the figure shows

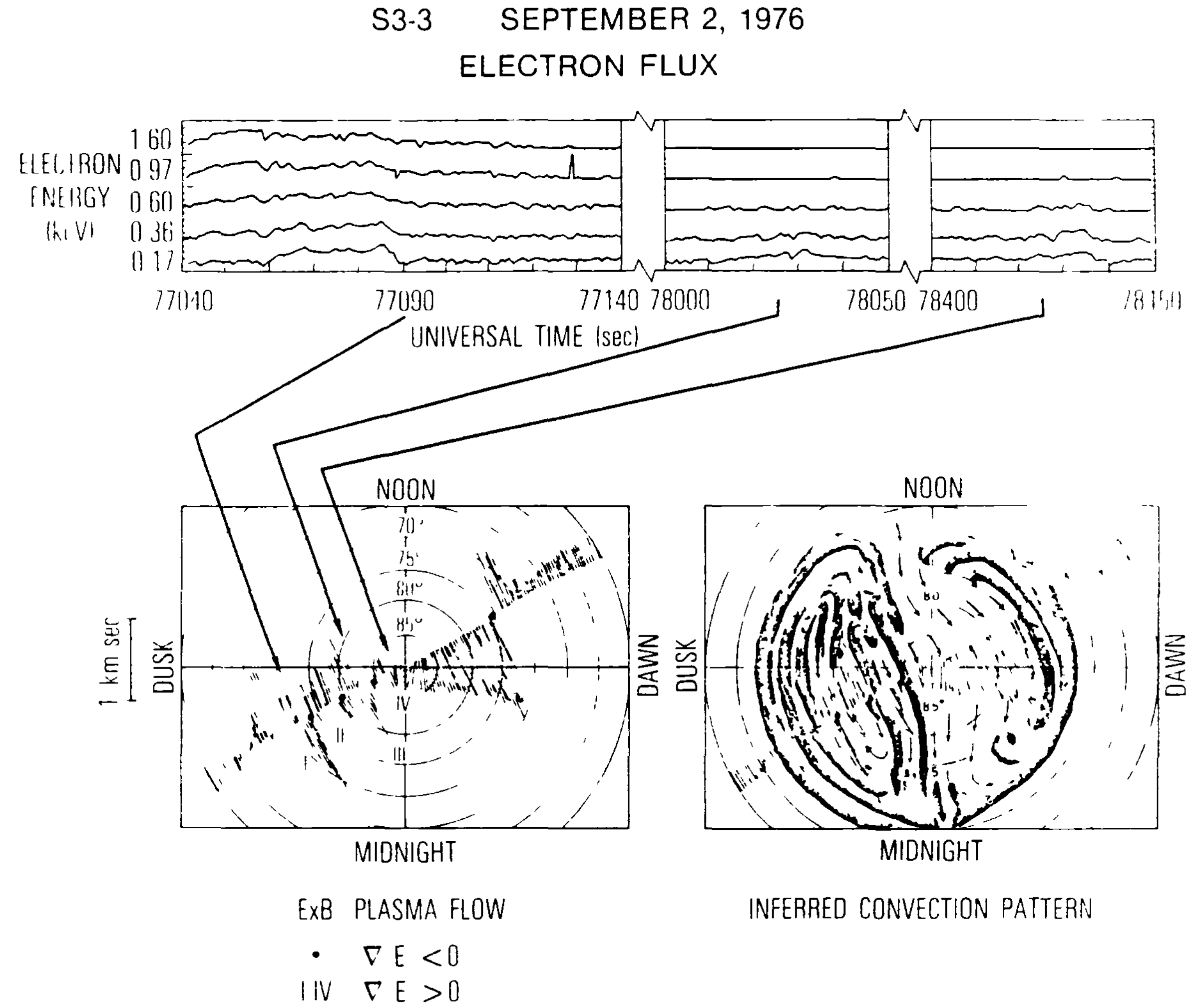

Fig. 1. A composite diagram showing energetic electron flux, local plasma flow, and inferred polar-cap convection patterns for a dawn-dusk polar-cap crossing of the S3-3 satellite on Day 246, 1976. Energetic electron data are shown for periods corresponding to flow reversals I, III, and IV. Note that only the flow component perpendicular to the satellite path is plotted in the lower left panel.

the energetic electron data acquired by the Aerospace electrostatic analyzer during three of these transition periods. Differential number fluxes in five low-energy channels are plotted (tic marks indicate decades in flux, with a maximum value of 10^9/cm^2 sec ster keV in each individual energy panel).

The first enhancement, centered on 77090 seconds UT (at an invariant latitude of 72°) is the poleward extent of the nominal dusk auroral zone, with intense precipitating flux observed well above 1-keV energies. The precipitating flux at energies .17 - 1.6 keV decreases by about three orders of magnitude over the period 77090 - 77140, as the spacecraft enters what appears to be a region of open field lines over the polar cap. Two other precipitating electron enhancements are observed at higher latitudes, but extending only to < 360 - 600 eV energies (very characteristic of magnetosheath precipitation). These two enhancements, at 82.5° and 87° invariant latitude, are both coincident with sunward to anti-sunward flow reversals.

Upflowing ion beams of 400 eV - 1 keV energies were observed in the first (low latitude) enhancement, but no upflowing ions with energies above the 90-eV instrument threshold were observed in the higher-latitude enhanced regions. Upflowing ion beams have been observed over the polar cap by the S3-3 satellite during disturbed conditions (e.g., Gorney et al., 1981). No energetic plasma enhancement was observed coincident with the flow reversal labeled II at 78° invariant latitude.

In developing a consistent theoretical description of this set of observations, the following specific observations must be explained:

1. Multiple $\vec{E} \times \vec{B}$ plasma flow reversals in the dusk sector of the polar cap.

2. Hot ($\geq$ 1 keV) electron precipitation and upflowing ions at the low-

latitude $\vec{E} \times \vec{B}$ flow reversal (Λ = 72°) from sunward to anti-sunward directions. This flow reversal, together with the keV electron precipitation, is to be identified with the usual 2-cell convection reversal boundary and the normal inverted-V precipitation.

3. Two apparently separate regions of relatively cool (< 400 eV) electron precipitation on extremely polar field lines, coincident with sunward to anti-sunward flow reversals. These multiple flow reversals, poleward of the normal auroral oval, require a reexamination of the plasma flow pattern.

4. No observed precipitation of electrons (> 70 eV) at the flow reversal labeled II, just poleward of the nominal auroral oval.

In the following section we describe a simple conceptual model which consistently incorporates each of the above observations, as well as related optical auroral features over the polar cap.

III. LARGE EDDIES OF MAGNETOSPHERIC CONVECTION

Instability of the shear flow at the magnetospheric convection reversal boundary has been suggested to account for wave observations at the magnetopause [see summary in Southwood, 1979]. Shear flow vortices of small scale ($\leq$ 100 km in the ionosphere) associated with the discrete arc, known to be related to the convection reversal boundary, have been observed [Davis and Hallinan, 1976; Hallinan, 1976]. Haerendel [1978] has also suggested existence of small-scale eddies at the cusp. These phenomena established the dynamic and variable behavior of the convection reversal boundary on the smaller spatial scales. On larger spatial scales ($\gtrsim$ 1000 km), little attention has been paid to the distortions of the convection reversal boundary, although it is often remarked that deep auroral folds, which are commonly seen in DMSP photographs, can easily be of such a scale [see, for example, cover photograph of Geophysical Research Letters, vol. 8, number 4, April 1981]. If the observed relationship between discrete arcs, inverted-V structures in particle precipitation, and the characteristic signature of inward-pointing DC electric fields is assumed, these deeply folded arc structures would indicate that the convection reversal boundary (indicated by the DC electric field signature) is also folded into "tongues" of convection eddies very much evident at the analogous shear flow confluence of two streams.

Independent of shear flow instability, suggestions that the convection flow pattern may be very different during conditions of northward IMF have been made [e.g., Reiff, 1982]. These interpretations suggest that different magnetic field merging patterns would drive unusual convection flows. However, it remains to be seen what kind of merging pattern (or shear flow) would produce the complex reversals as described in the previous section.

In this paper, we focus on the plasma and electric field relationships of polar cap multiple flow reversals rather than on the origins of these unusual flow patterns. We assume that the polar cap flow reversals are due to multicellular eddies and examine its consequences in terms of S3-3 observations of plasma and DC electric fields in the polar cap and in terms of some current theoretical notions of arc formation. Obviously, we are at the stage of examining observational consequences of hypotheses. We do not make presumptions as to the development of such a highly distorted state of flow reversal boundary from its origin in small-amplitude instability or in magnetic field merging. The Kelvin-Helmholtz instability and unusual magnetic field merging are obvious choices as generators of such a state; however, we shall not attempt to tackle the theoretical question of eddy development here.

Given the existence of deep convection eddies, the first consequence is that "tongues" of hot (>> 10 eV) plasma of plasmasheet or magnetosheath origin (depending on the location of the eddy) can intrude into the anti-sunward flow of the polar cap. A satellite, such as S3-3 or DE-1, flying through the polar cap near the dawn-dusk meridian will see distinct regions of flow reversal (DC electric field reversal) associated with alternating characteristics of plasma. This signature is illustrated in the top panels of Fig. 1. In the lower right panel of Fig. 1, the corresponding hypothetical flow structure associated with the observed DC field structure is shown. Obviously, since S3-3 made a single cut across the flow structure in the polar cap, the flow structures away from the cut are constructions based upon our hypothesis of deep convection eddies; therefore, Fig. 1 is to be interpreted in terms of its concept rather than in terms of its detailed structure away from the satellite track. Unless one assumes very drastic postulates, we cannot see presently how multiple polar cap flow reversals (a very common occurrence in S3-3 data) can alternately be generated in forms other than eddies.

Assuming the flow structure shown in the bottom panel of Fig. 1, present theory of the discrete arc and inverted-V structure predicts a definitive relationship between the characteristics of the flow reversal boundaries and the occurrence of these plasma structures on them. Kinetic theories of the discrete arc and inverted-V structure [Chiu and Cornwall, 1980; Lyons, 1980, 1981; Chiu et al., 1981] are by and large agreed that these plasma features require inward-pointing DC electric field signatures ($\nabla \cdot \vec{E} > 0$) at the reversal. Reversals satisfying this condition are marked by Roman numerals on Fig. 1. No electron precipitation is expected on reversals marked by black dots because these do not satisfy the DC field signature. Reversal I is the regular discrete arc marking the usual boundary between sunward magnetosheath flow and the polar cap.

In addition, Chiu et al. [1981] estimated the depth of the inverted-V parallel potential drop $\Delta\phi$ to be approximately related to its approximate width $\lambda \approx \sqrt{(\Sigma_0 m_e \bar{v}/\bar{n}e^2)}$, where Σ_0 is the ionospheric height-integrated conductivity, $\bar{v}$ and $\bar{n}$ are average speed and density of electrons above the structure:

$$\Delta\phi \simeq \int_0^\infty d\chi\, e^{-\chi/\lambda}\, E_{\perp 0}(\chi) \sim \bar{E}_{\perp 0}\, \lambda \qquad (1)$$

In (1), $\bar{E}_{\perp 0}$ is the electric field magnitude $E_{\perp 0}(\chi)$ averaged over a perpendicular distance $\chi \sim \lambda$. Thus, the parallel potential drop depends on the perpendicular electric field strength and the energy of the electrons above the drop. Based on this relation, we would expect that the reversal II in Fig. 1, involving cool polar cap plasma, should be weaker than the others even though the DC electric field signature requirement is satisfied.

Comparison of these theoretical expectations with the electron data in the top panels of Fig. 1 shows that indeed electron precipitations of several hundred eV are found at reversals III and IV; and there is an absence of electron precipitation at all other polar cap flow reversals not satisfying the above conditions. Thus, a simple hypothesis about the magnetospheric convection flow structure has allowed us to tie together complex electric field and plasma data in the polar cap and to relate them to discrete arc formation theory at the oval. Although there is no optical imagery to confirm that polar cap arcs are located at reversals III and IV, field-aligned precipitation of electrons (~ 200 eV) over inverted-V scales could produce some luminosity in the otherwise dark polar cap.

IV. POLAR-CAP ARC STRUCTURE

Although cases of flow reversal and associated hot electron precipitation in the polar cap are quite common in S3-3 data, we recognize that hypothesized large-scale eddy intrusion of magnetosheath plasma flow into the polar cap is by no means established to be the generator of polar-cap arcs. However, because it has demonstrated its power of data organization, it is perhaps worthwhile to explore further implications of this simple working hypothesis.

a. If the deep eddies are not occluded (cut off from the magnetosheath flow), the structure of the polar cap arc system will necessarily be offshoots from the oval arcs. DMSP photographs, such as the Geophysical Research Letter cover photograph referred to above, indicate that this type is very common. If the deep eddies can be occluded, then the vortical flow of the hot plasma eddies can migrate unpredictably in the anti-sunward polar-cap flow, not unlike occluded low-pressure areas in the westerly tropospheric flow. If such large eddies can occasionally migrate across the polar cap, a configuration somewhat similar to the Θ-aurora [Frank et al., 1982] may arise.

b. If the flow eddies are not offshoots from the regular convection reversal boundary, e.g. driven by unusual magnetic field merging, then the θ-configuration requires further elucidation since the oval arcs are missing in this case.

c. In either type of eddy, occluded or non-occluded, the plasma originates from the region of the "break" at the flow reversal boundary, which can be anywhere on the oval. However, Akasofu and Kan [1980] pointed out that arc morphology seemed to fall into dayside and nightside arc systems, with a "break" in the multiple arc systems near the dawn-dusk meridian. DMSP photographs also give the impression that the preferred locations of deep "folds" in arc structures are at the magnetospheric flanks. If so, then our hypothesis would clearly identify the origin of the hot polar cap plasma as magnetosheath-dayside (100 eV) or plasmasheet-nightside (keV), according to the location of the "break" — a consequence easily tested by simultaneous plasma and optical imagery data.

d. Although we have repeatedly used the analogy of neutral fluid shear flow, plasma convection involves the magnetic field and is, therefore, different. If the frozen-in limit holds, then together with the plasma intrusion, some closed field lines at the flanks, which may be exposed to the hot plasma, can intrude into what is usually regarded as the polar cap. The plasma signature of such cases would be quite distinct, marked not only by energy but by double loss-cones. Polar cap plasma with double loss-cones are often seen in S3-3 data. On the other hand, microscopic plasma processes may destroy the frozen-in condition, then the eddying plasma can slip off into polar cap field lines so that locally, at least, the distorted convection reversal boundary does not mark the magnetic field topology. Such a possible situation may occur at the site of IMF B_y, merging at the flanks of the magnetosphere. In this regard, Lassen and Danielsen [1978] noted the strong positive correlation of polar cap together with oval arc occurrence with the magnitude of IMF B_y. Future study will probably clarify the relationship between IMF B_y and the generation of the large-scale convection eddies. It should be noted that IMF B_y for the case shown in Fig. 1 is quite large (average $B_y \sim 1.5 - 3.50\ \gamma$).

e. We have searched published ionospheric measurements of polar-cap flow [e.g., Heelis and Hanson, 1980] and found essentially little mention of multiple flow reversals comparable to Fig. 1, which is measured at ~ 5000 km altitude. If this proves to be true, then polar cap arcs would again be similar to oval arcs in that the parallel electric field in the inverted-V structure shorts out at several thousand kilometers altitude the potential excess at the 100 km scale, leaving the largest scale potential structure (anti-sunward flow) intact at the ionosphere.

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V. CONCLUSIONS

We show that a very simple hypothesis that large-scale plasma eddies may form at the convection reversal boundary and in the polar cap is able to organize electric field (plasma flow), plasma and possibly optical data into a coherent picture of polar cap arc structure. According to this picture, plasma flow eddies of magnetosheath-plasmasheet origin intrude into what is normally regarded as the polar cap. The eddy flows, embedded in the polar cap anti-sunward flow, create parallel electric fields, inverted-V's, and discrete arcs in their eddy convection reversal boundaries, whenever the appropriate conditions are met. If this hypothesis holds up under further tests, the high-altitude convection flow of the magnetosphere can no longer be regarded as a static two-cell pattern — a concept which has been assumed for more than two decades.

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