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A Study of the Spatial Scales of Discrete Polar Auroral Arcs

Prepared by

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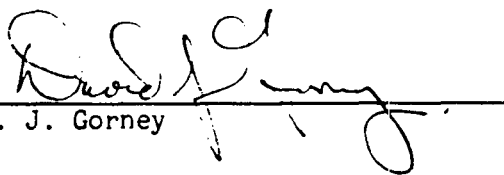
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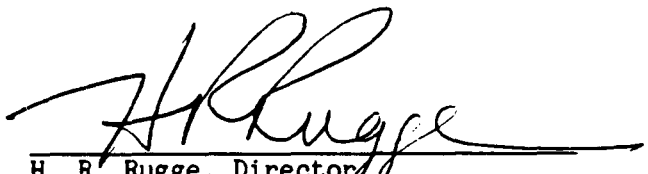
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ABSTRACT

Recent theoretical works have dealt with the identification and evaluation of the physical processes that determine the characteristic scale sizes of discrete auroral arcs. It is broadly acknowledged that a characteristic spatial width of ~100 km (at ionospheric heights) results naturally from the ionospheric mapping of the high-altitude magnetospheric convection electric field. However, recent analysis of the spatial power spectral distributions of electric and magnetic field variations has revealed structure at much smaller spatial scales. In this analysis, we use precipitating auroral electron data from the J-package sensor on the Defense Meteorological Satellite Program satellite to study the spatial scale sizes and size distributions of polar auroral arcs. A monotonically decreasing inverse-wavelength spectrum with a slope near unity is common, with no strictly "preferred" scale sizes, although the scale spectrum does flatten at scales larger than ~100-200 km. Typical observed widths of the auroral arcs tend to be much smaller than the resistive scale length, and the observed widths do not have a strong dependence on local ionospheric parameters.

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I. INTRODUCTION

Several recent theoretical works have dealt with the identification and evaluation of the physical processes that determine the characteristic sizes and size distributions of discrete auroral arcs (Refs. 1-5). It is broadly acknowledged that a characteristic spatial width of ~100 km (at ionospheric heights) results naturally from the resistive mapping of the magnetospheric convection electric field into the ionosphere. Recent analysis of the spatial spectral distributions of electric and magnetic field variations (Ref. 6) has revealed the presence of structure over a range of smaller spatial scales. These observational results have stimulated theorists to consider processes that lead to a spectrum of auroral scales (Refs. 4,5,7). The purpose of the present observational study is to perform a clear parametric test of existing theories of auroral scales.

For this observational study, we have used precipitating auroral electron data from the SSJ/4 instrument on Defense Meteorological Satellite Program (DMSP) F6. We have chosen data samples that allow a comparison of auroral scales under sunlit and dark ionospheric conditions. The time period chosen for study is very quiet. Precipitating electron fluxes only rarely exceeded $1 \text{ erg/cm}^2\text{sec}$ during the study interval. A period of quiet arcs was chosen to better discriminate the effects of background ionospheric conductance on the auroral spatial scale.

II. OBSERVATIONS

The DMSP SSJ/4 instrument obtains complete precipitating electron and ion energy spectra once each second over the energy range from 30 eV to 30 keV. The time period chosen for study is a period of continuous high-latitude auroral arc activity on 11 January 1983. Detailed characteristics of the auroral activity and interplanetary conditions during this time period are discussed elsewhere (Refs. 8,9). The period was chosen for a number of reasons. First, auroral arcs are present over a wide latitude range, and the arcs occur fairly continuously over a several hour interval. Second, the auroral arcs, although numerous and continuous, are very weak and (presumably) do not alter the background ionospheric conditions significantly. Third, the auroral arcs are linear in configuration and are more or less sun aligned. This orientation allows thorough sampling of the arc structure from the DMSP dawn-dusk orbit. Finally, lighting conditions at this time were such that the DMSP ionospheric track was completely sunlit in the southern polar region and completely dark in the north. Auroral arcs were present over both poles.

Figure 1 shows the DMSP trajectories in geomagnetic latitude-local time coordinates. The orientation of the solar terminator is indicated with the heavy shadowed line. The two left panels (A,C) show northern polar passes, with the trajectory completely in darkness. The right panels are southern polar passes, completely in sunlight. The individual polar crossings occur about 50 min apart. During this period, DMSP passes very close to the geomagnetic pole, providing complete latitude coverage.

Figure 2 shows linear plots of the precipitating electron number flux for each of the four intervals shown in Fig. 1. The horizontal bracket in panel A shows a 100 km ionospheric scale size for reference. All four data samples show the occurrence of multiple (10-30) narrow discrete auroral arcs distributed across the entire polar region. The flux enhancements have scale sizes comparable to the resolution of the instrument (-7 km).

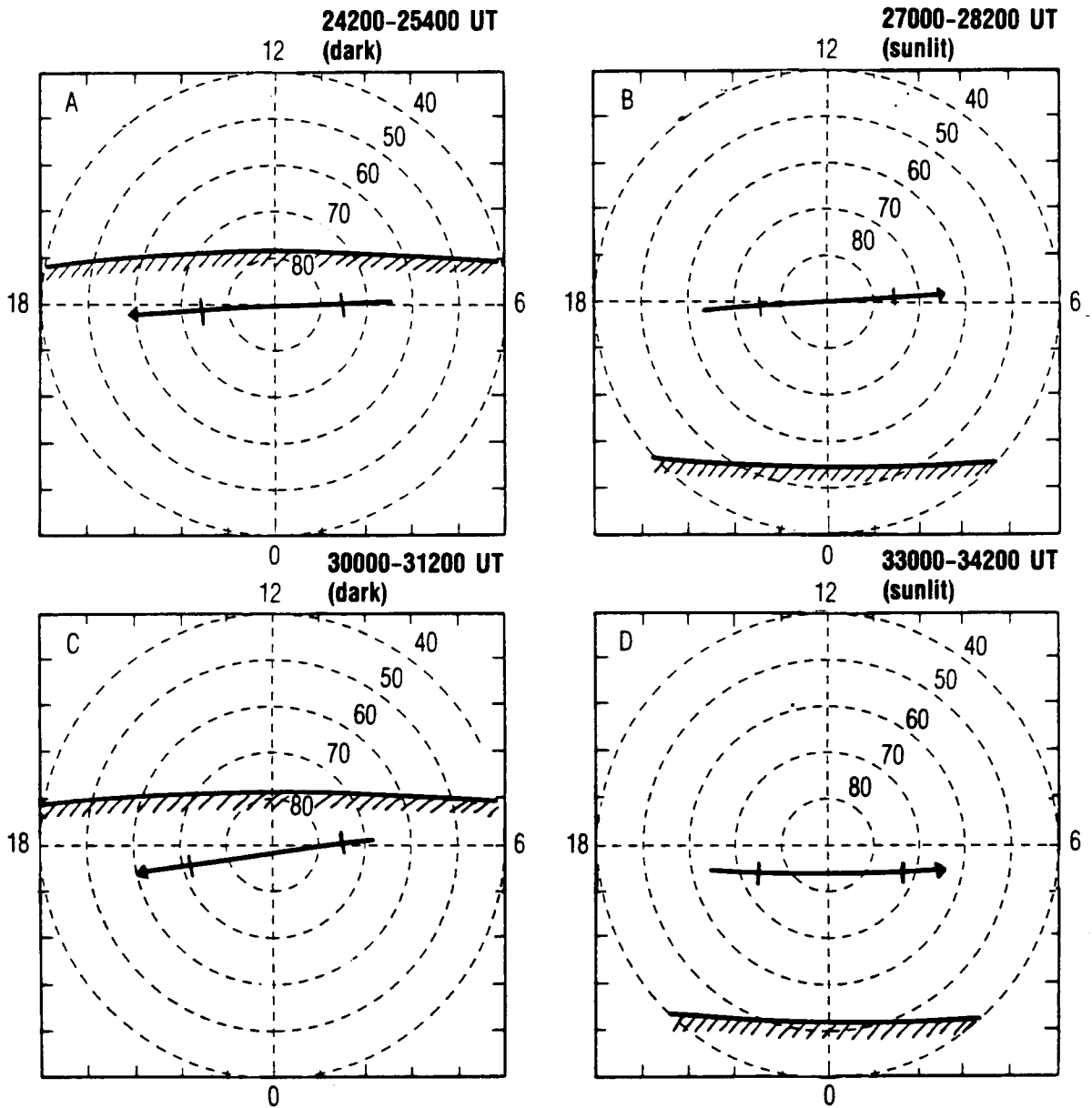


Fig. 1. Trajectories of the DMSP F6 Satellite in Geomagnetic Latitude-Local Time Coordinates for Four Polar Passes

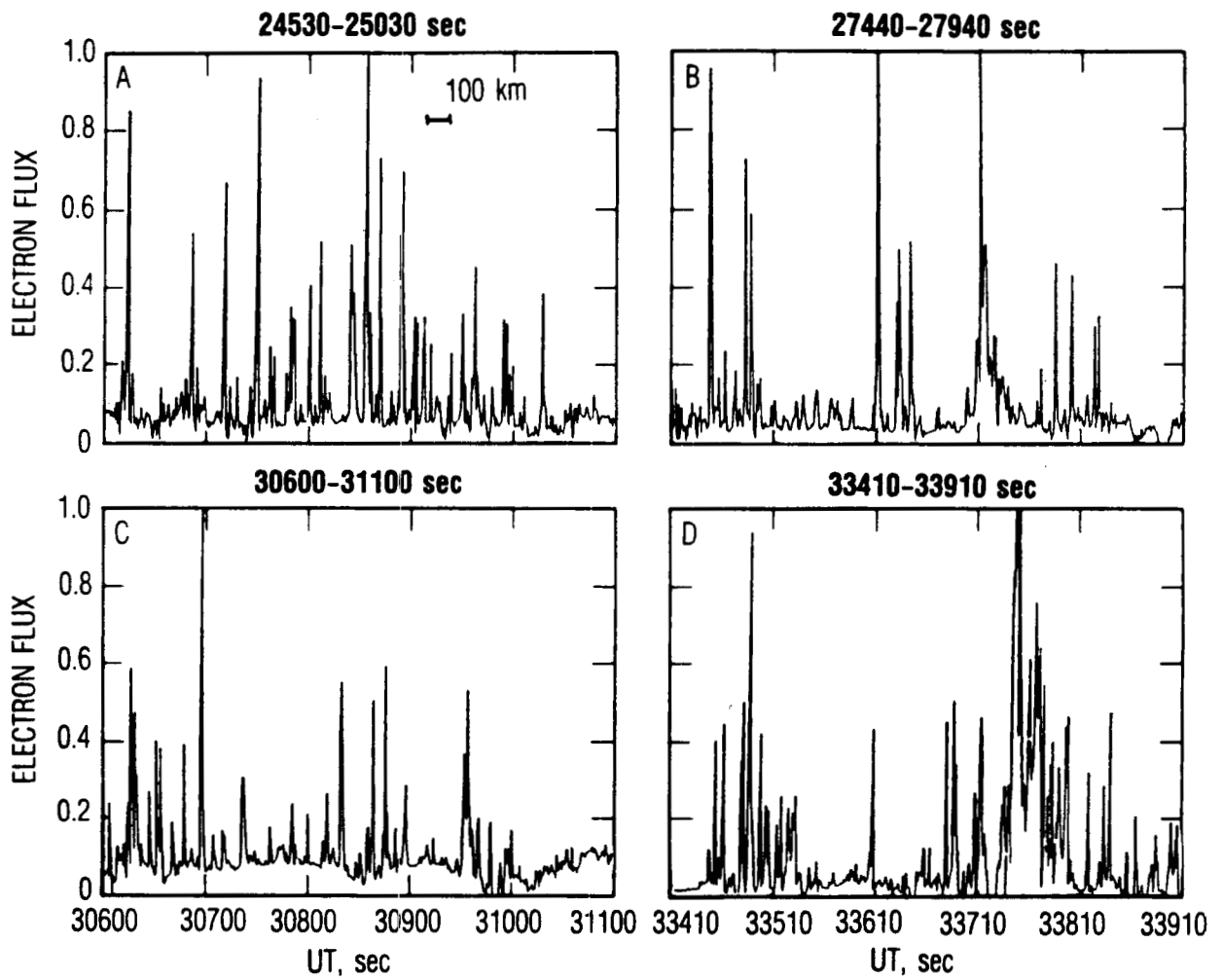


Fig. 2. Linear Plots of the Precipitating Auroral Electron Flux for the Four Polar Crossings of DMSP Shown in Fig. 1

The separation between individual discrete features ranges from ten to perhaps hundreds of kilometers. The four data samples are qualitatively similar.

In order to determine the average width of the discrete auroral features, individual events from each of the four intervals were combined and averaged to compute an average shape and width. The average shape was computed by normalizing each event to its peak flux value and by centering each event about its peak flux position. The results of this averaging process are shown in Fig. 3. The vertical bracket indicates the statistical uncertainty for each case. In each case, the average event width appears to be very narrow (~ 7 km). The flux levels approach background values within 10 to 20 km of the center of the structure. No significant structure is discernible at scale sizes approaching 100 km.

Spectral analysis methods can also be used to examine the relative distribution of spatial sizes. This is particularly appropriate in this analysis, because several recent theoretical studies of the spatial scale problem utilize spectral representations of the problem. Figure 4 shows amplitude spectra of precipitating electron flux as a function of inverse wavelength mapped to ionospheric height. The four spatial spectra are quite similar. The spectra show an approximate k^{-1} dependence at high wave number and are relatively flat for wavelengths greater than about 100 km. No statistically significant peaks are present. Indeed, any subsets of the study intervals also showed no evidence for individual "preferred" scale sizes.

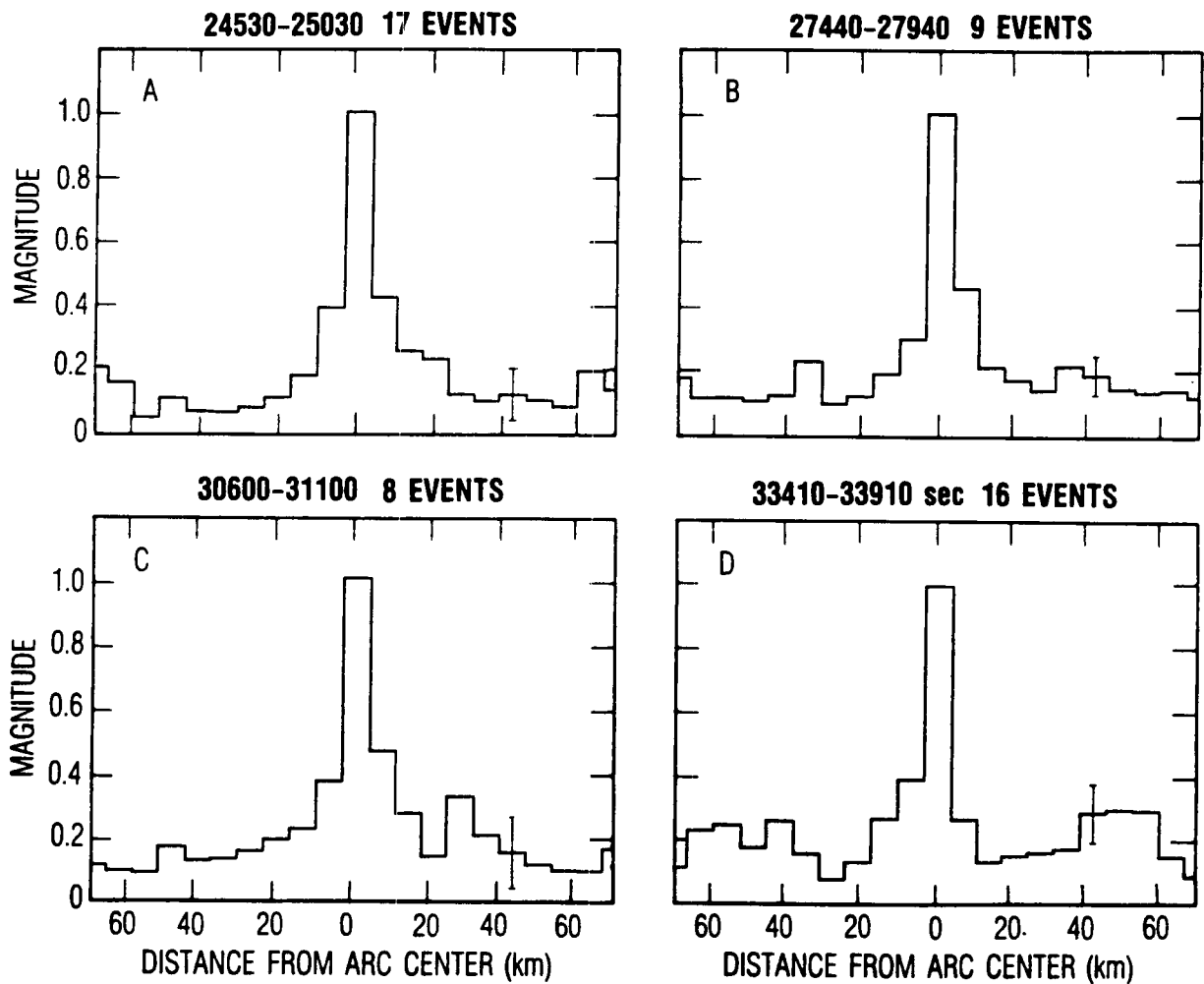


Fig. 3. Normalized Histogram Plots of the Average Shape and Width of the Individual Auroral Arc Events Shown in Fig. 2

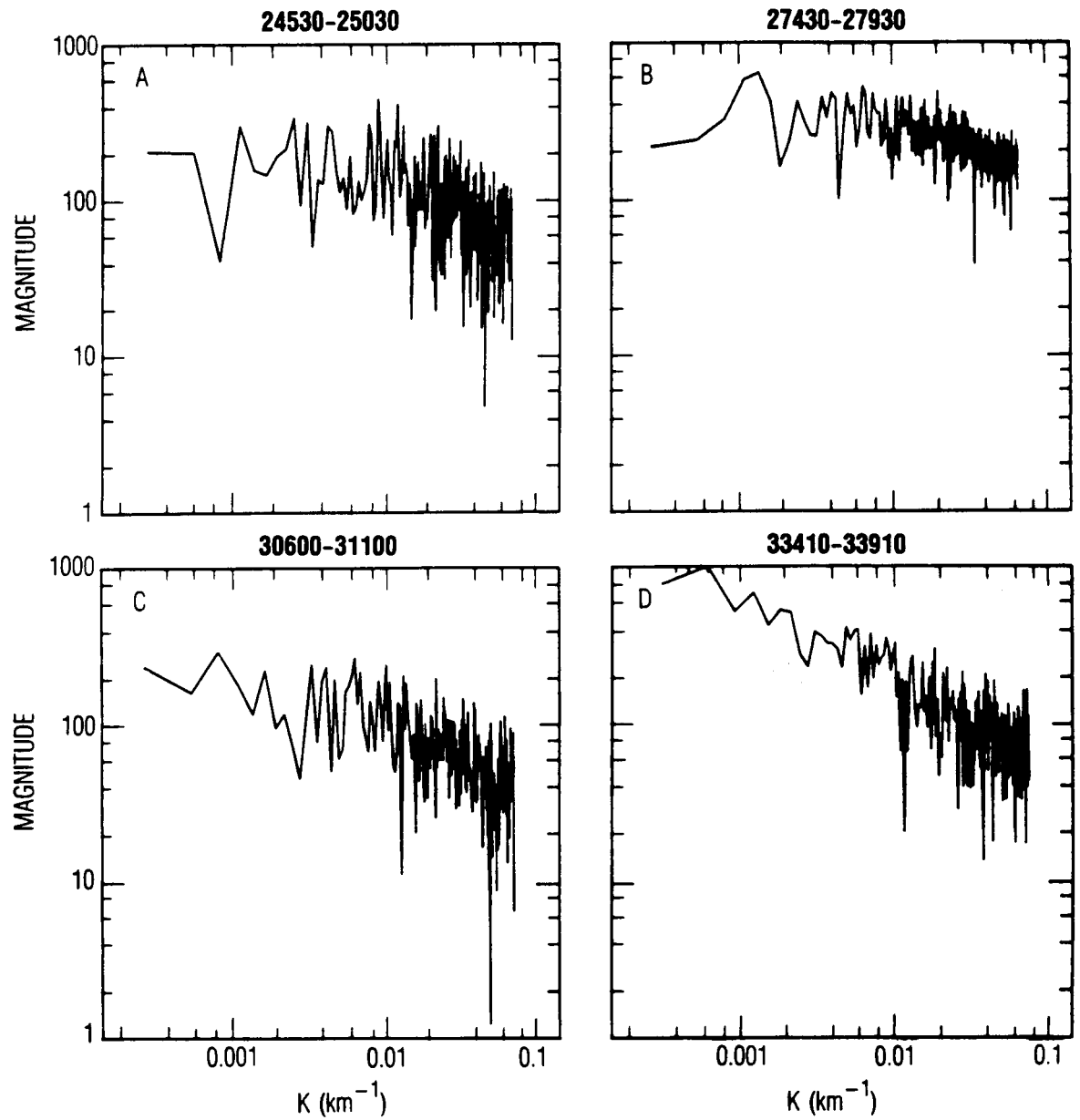


Fig. 4. Spectral Distributions of Precipitating Auroral Electron Flux from the Time Series Plotted in Fig. 2

III. INTERPRETATION

The notion that there should exist a scale size that characterizes discrete auroral features arises from the concept that the magnetic-field-aligned electric potential drops that cause auroral electron acceleration result from the inability of the magnetospheric electric field to map perfectly into the ionosphere. The imperfect mapping of the magnetospheric electric field results from the finite ionospheric conductance; thus the characteristic scale length can be thought of as the resistive scale length for the ionosphere-magnetosphere system. The existence of such a scale length can be demonstrated by considering the ionospheric Ohm's law, relating ionospheric current j to conductivity σ and electric field E :

$$j = \sigma \cdot E \quad (1)$$

Invoking current continuity (in three dimensions)

$$\nabla \cdot j = 0 \quad (2)$$

one obtains a relationship between the parallel (vertical) current j_{\parallel} , the height-integrated Pedersen conductivity Σ_p , and the horizontal gradient of the perpendicular electric field:

$$j_{\parallel} = -\Sigma_p \nabla \cdot E \quad (3)$$

Expressing the electric field as the gradient of a potential, and further assuming a linear relationship between parallel current and potential drop (Ref. 10), one obtains the relationship between the magnetic-field-aligned current and the magnetospheric electric potential:

$$(1 - \lambda^2 v^2) j_{\parallel} = \Sigma_p \nabla^2 \phi \quad (4)$$

where λ is the characteristic (resistive) scale of the system. The quantity λ depends on the characteristics of the ionosphere and on the characteristics of the current-carrying plasma. Specifically,

$$\lambda = (\Sigma_p / e^2 n)^{1/2} (4\pi m_e K_{th})^{1/4} \quad (5)$$

where n and K_{th} are the density and temperature of the current-carrying electron population. Note that the ionospheric Pedersen conductance affects the scale size fairly strongly. For typical values of n and K_{th} , the scale length is approximately 150 km in sunlight ionospheric conditions and about 15 km with a dark ionosphere (completely neglecting the effects of the particle precipitation on the ionospheric conductance; that is, for weak auroras). For more intense auroras, the scale size approaches 100-200 km, regardless of ionospheric illumination.

The average scale size of the individual auroral features in this study was much smaller than even the smallest value predicted by the resistive mapping equation. However, this should not be viewed as a failure of the theory to represent the true spatial structure of discrete auroras. Rather, the discrepancy has to do with a common and long-standing misinterpretation of the physical meaning of the predicted scale size. This point is best elucidated by viewing Eq. (4) in terms of its Fourier components:

$$j_{\parallel k} \sim \phi_{\parallel k} \sim \frac{k^2 \lambda^2}{1 + k^2 \lambda^2} \phi_k \quad (6)$$

Thus, if one regards the magnetospheric convection electric field ϕ in terms of its distribution in "k-space", Eq. (6) shows how spatial structure in ϕ results in a spatial scale distribution of parallel currents, or equivalently, parallel potential drop. More importantly, Eq. (6) shows the role of the spatial scale parameter λ in determining the relationship between the spectra of electric potential and current. For small k (wavelengths longer than λ), magnetospheric electric field structure does

not lead to parallel currents, while for large k (wavelengths smaller than λ), all structure in ϕ leads to an identical spatial distribution of parallel currents and parallel potential drops. The quantity λ is simply the break point in the spatial spectrum but by no means represents a unique "preferred" scale for the system. The formulation predicts that small scale auroral features should be expected, provided that small scale structure exists in the magnetospheric potential and that auroral features should not exceed the 100-200 km characteristic scale size.

Thus, these theoretical results and interpretations appear to be completely consistent with the data presented here. Furthermore, the spectral interpretation is borne out in previous statistical studies of inverted-V scale sizes (Ref. 11) and in studies dealing with the mapping of electric fields from high to low altitudes (Ref. 6).

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