fields, static randomness, etc. Thus, it is expected to become an important theoretical tool for studying many-body systems, especially narrow-band materials[8] (e.g., NiS) and impurity bands in crystalline semiconductors.[9]

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[8]We are using the present scheme to study the behavior of NiS; preliminary results agree well with experimental data and strongly suggest that a quantitative understanding of this interesting and controversial subject is at hand.

[9]Employing an extension of the approach presented here, we are currently investigating the long standing problem of negative magnetoresistance in impurity bands of crystalline semiconductors; our preliminary results are very encouraging.

Observations of Paired Electrostatic Shocks in the Polar Magnetosphere*

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dc and ac plasma-density and vector—electric-field detectors on a polar orbiting satellite have measured spatially confined regions of extremely large (~ ½ V/m) electric fields in the auroral zone at altitudes below 8000 km. Such regions frequently have double structures of opposing electric fields containing characteristic and different wave spectra internal and external to themselves. These structures are identified as paired electrostatic shocks which are associated with electrostatic ion cyclotron wave turbulence.

The S3-3 satellite was launched during the summer of 1976 into a nearly polar orbit with perigee and apogee altitudes of 260 and 8050 km, respectively. On-board instruments have made the first *in situ* measurements of dc electric fields at auroral latitudes and altitudes where particle-acceleration, kilometric-radiation-generation, and anomalous-resistivity processes are thought to occur. The Berkeley experiment on this satellite measures the dc and ac plasma density and vector electric field. It has observed spatially confined regions of extremely large electric fields whose structure suggests paired electrostatic shocks that may be associated with particle acceleration, auroral arc formation, and wave production.

The electric-field detector consists of three orthogonal pairs of separated spheres whose measured potential differences yield three orthogonal components of the static or fluctuating electric field. Four of the spheres are located at the ends of four 18-m wire booms that are maintained in the satellite spin plane by centrifugal force. The remaining pair of spheres are oriented along the vehicle spin axis on 3-m rigid booms. By ground command, a sphere on a wire boom may be converted from the potential-measuring mode to a conventional Langmuir probe whose collected dc and ac currents yield the plasma density, temperature, and density fluctuations.

The magnitudes of electric fields expected at the satellite may be estimated by extrapolating the extensive ionospheric data[1] in altitude by assuming that magnetic-field lines are electric equipotentials. On this basis, the largest iono-

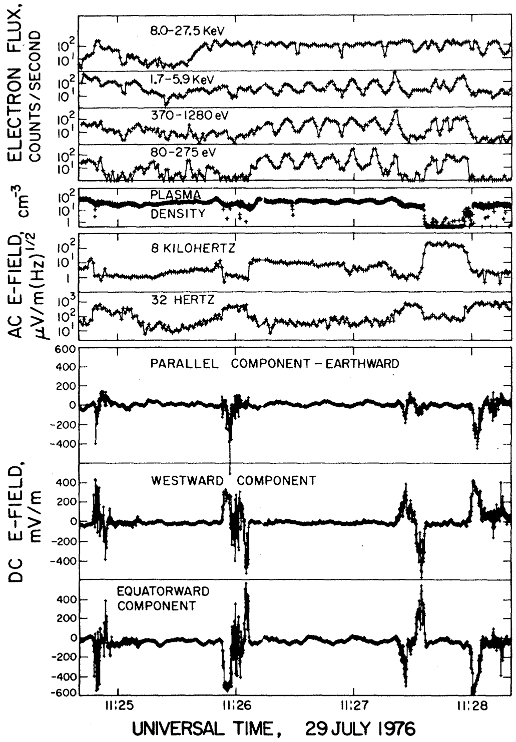

FIG. 1. Field and particle measurements made on a satellite during its poleward-bound passage through extremely large dc-electric-field regions in the northern auroral zone. The particle data are modulated at twice the satellite spin frequency.

spheric electric fields (~ 100 mV/m in the north-south component and ~ 50 mV/m in the east-west component) correspond to perpendicular field components of ~ 25 mV/m at an altitude of 6000 km. According to the present satellite observations, fields larger than this often exist over much of the polar region at such altitudes, and spatially confined regions of fields at least an order of magnitude larger are observed. Thus, the lower ionosphere must be electrically decoupled from plasmas existing at altitudes of a few thousand kilometers and the concept of "frozen-in" magnetic-field lines cannot be universally applied in the magnetospheric plasma.

One of the best observations of large fields is given in Fig. 1, in which the lower three curves are electric-field components measured in a magnetic-field-oriented, nonrotating frame of reference at an altitude of 7600 km, a magnetic latitude near 76°, and a local time near dusk. At universal times (UT) near 11:24.8, 11:26, and 11:27.6, large, oppositely directed, electric fields are observed with the double peaks separated by a region of relatively small field.

The measured electric fields are oriented predominantly perpendicular to the magnetic field, and the two perpendicular field components are roughly proportional to each other. This proportionality requires the electric-field vector to be approximately located in a plane that includes the magnetic field and the direction 35° west of magnetic north.

The parallel electric-field component of Fig. 1 is often several hundred millivolts per meter; and, in these particular events, it is primarily directed away from Earth. The largest average parallel field, in the event near 11:28 UT, has a magnitude that is uncertain because one of the electric-field detectors was saturated.

Data from about 100 high-latitude satellite passes have been surveyed with the following conclusions on the general region of occurrence of these double electric-field structures: (1) Electric fields larger than ~120 mV/m are seen on about half of the high-latitude passes. Their occurrence is positively correlated with magnetic activity. They are found at all altitudes (2000–8000 km) and local times (0500–2300) reached by the satellite and occur most frequently on magnetic-field lines having $L \sim 7-20$. (2) The fields often vary on time scales less than 10 sec and there are many structures in a small spatial region. Thus, the typical double-structure field pattern is not as evident as that illustrated in Fig. 1. (3) The intense dc fields occur in regions of extreme plasma turbulence, i.e., where the broadband relative density fluctuations are ~20% and the broadband ac electric field is ~20 mV/m. (4) They occur in the general region where the on-board altitude magnetometer indicates the presence of magnetic-field–aligned currents greater than 10^{-6} A/m^2.

The particle populations in these large-field regions have the following characteristics[2]:
(1) Oxygen and hydrogen ions are accelerated to energies of a few kilovolts between the satellite and the ionosphere, as has been reported.[3]
(2) Field-aligned beams of ~100-eV electrons are often observed within the regions of large electric field. This suggests that field-aligned currents may be carried by 100-eV electrons which are streaming in the big-field regions.
(3) Low-energy electrons are often excluded from the central region of the paired electric-field structures, as evidenced by the data of Fig. 1. (4) The plasma density is sometimes diminished inside and/or adjacent to the electric-field structures, as the data of Fig. 1 illustrate.

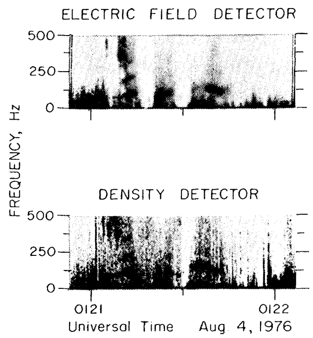

FIG. 2. Frequency-time spectrogram of density fluctuations and the ac electric field measured at a time different from that of Fig. 1, but during which the satellite passed through a region of large electric fields while broadband real-time data were being transmitted. The periodicity in the data is due to a combination of temporal variations and rotation of the spacecraft in the polarized field.

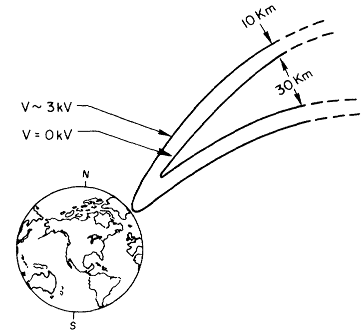

FIG. 3. Model of the equipotential contours associated with paired regions of large and oppositely directed electric fields.

The wave turbulence in the vicinity of the electric-field structures is illustrated by the two ac curves in Fig. 1. Inside the dc structure the wave spectrum is steep, with most of the wave energy appearing at frequencies $\lesssim 200$ Hz. Adjacent to the dc structures, relatively flat spectra with significant power at frequencies ~ 10 kHz are seen. Properties of the waves having steep spectra are as follows: (1) The wave electric-field component parallel to the local-magnetic-field direction is at least an order of magnitude smaller than the perpendicular component. (2) The waves are electrostatic since significant density fluctuations are always observed. (3) As illustrated in Fig. 2, frequency-time spectrograms of the electric-field and density fluctuations exhibit peaks in the power spectrum near the local hydrogen-ion cyclotron frequency and its harmonics. (4) The ratio of the density fluctuations to the electric-field fluctuations at a given frequency yields the wave number at that frequency.[4] For the event of Fig. 1, $k \approx 0.05\ \mathrm{m}^{-1}$ at the local ion cyclotron frequency of 110 Hz.

The above data are consistent with the observation of electrostatic ion cyclotron waves, since this mode is electrostatic, is polarized nearly perpendicular to the magnetic field, and has frequencies nearly equal to the hydrogen cyclotron frequency; and its harmonics and has a fastest growing k vector at the inverse of the ion cyclotron radius,[5] as was observed. Furthermore, the electron drift, obtained from the field-aligned-current and density measurements to be the order of the electron thermal speed, yields an ion-cyclotron growth rate which is $\sim 20\%$ of the ion gyrofrequency or a growth time of ~ 50 msec if the electron and ion temperatures are equal.[6]

Since measured magnetic-field variations are small, the spatial pattern of the double structures may be imagined through constructing equipotential contours of the electric field, as drawn for illustrative purposes and not to scale in Fig. 3. The dimensions in this figure are obtained from the satellite traversal time under the assumption that the field structures are stationary in space. The experimental data do not indicate whether, how, or where the contours close above the satellite. That the structures are closed somewhere above the spacecraft is suggested by the frequent absence of low-energy electrons internal to the structures, as illustrated in Fig. 1. The lower-altitude closure of the structure in Fig. 3 has been drawn in the ionosphere to be consistent with earlier observations of parallel electric fields at low altitudes[7] and because confined regions of large fields have been seen on the present satellite at all altitudes between the lower observational limit of about 2000 km and apogee at 8000 km.

The data and the model of Fig. 3 exhibit large amplitude discontinuities in small distances. Hence, one may interpret such structures as electrostatic shocks. Swift[8] has proposed a model for the acceleration of auroral electrons by steady-state oblique electrostatic shocks supported by the current-driven electrostatic ion-cyclotron instability. The present data are in good agreement with this theory since the observed shock thickness is the order of an energetic ion gyroradius and since electrostatic ion cyclotron waves are observed. The present data are inconsistent with direct observation of double layers to the extent that double layers are defined to be associated with ion acoustic waves and to have thicknesses that scale with the Debye length.[9]

Additional properties of paired electrostatic shock structures are the following: (1) The ~3-kV potential drop in the shock structure, which must also occur somewhere along the magnetic field line, is consistent with the potential required to accelerate auroral electrons to observed energies. (2) The satellite transit time through the events of Fig. 1 suggests that paired electrostatic shocks can exist for at least 10 sec, although other examples suggest a shorter minimum time scale. (3) Since there is a nearly longitudinal direction along which the perpendicular electric field is small, the equipotential contours of Fig. 3 may be thought of as a cross-sectional view of an extensive, nearly longitudinal configuration. (4) Several paired shock structures are typically observed over a narrow range of latitudes. Those of Fig. 1 scale to ionospheric separation distances of ~50 km, which is a larger latitudinal separation than that frequently observed in the satellite data.

The above four properties also describe spatial and temporal features of auroral arc configurations. Hence, it is plausible that particle acceleration and auroral forms are produced by the observed electrostatic shocks.

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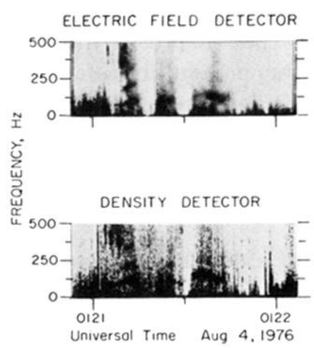

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