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THE STRUCTURE OF THE HIGH-LATITUDE IONOSPHERE AND MAGNETOSPHERE

From a variety of experimental observations, it is known that the high-latitude ionosphere and magnetosphere, from the auroral zone into the polar cap, is a nonequilibrium medium containing structure with scale sizes ranging from hundreds of kilometers to centimeters. Both magnetospheric and ionospheric sources have been proposed to account for this structure.

INTRODUCTION

The earth's high-latitude (auroral and polar) ionosphere is an important element in solar-terrestrial energy-transfer processes.[1-3] As a major terrestrial sink for many solar and magnetospheric events, the high-latitude ionosphere has characteristic features that can be traced to such seemingly remote phenomena as solar flares, radiation-belt/wave-particle interactions, and magnetospheric substorms.

In considering the multitude of solar-terrestrial plasma interactions, it is important to recognize that the high-latitude ionosphere is not altogether a simple receptor of various energy deposition processes. The high-latitude ionosphere can play an active feedback role by controlling the conductivity at the base of far-reaching magnetic field lines and by providing a plasma source for the magnetosphere. Indeed, the role of the ionosphere during magnetospheric substorms is emerging as a topic for meaningful study in the overall picture of magnetospheric-ionospheric coupling.

The accessibility of the ionosphere provides the opportunity for rather detailed investigations with combinations of in situ diagnostics and remote sensing techniques. Thus it provides the space physics community exciting challenges in studying many of the dynamic and unstable ionospheric plasma states. Indeed, there are regions of the earth's ionosphere that are more irregular than not, more dynamic than quiescent, and more unstable than was previously appreciated.

The study of ionospheric structure, while traditionally focused on density irregularities, more generally includes irregularities in density, temperature, ion composition, and fields. The study of irregularities in the ionospheric F region has divided itself naturally into three regimes: the low, middle, and high geomagnetic latitudes. These regimes have fundamentally different sources for the irregularities, which are associated with the degree of coupling to higher altitude magnetospheric phenomena. The coupling is related, of course, to the orientation of the geomagnetic field as a function of magnetic latitude. At low latitudes near the equator, where the geomagnetic field tends to be horizontal, coupling to higher altitude magnetospheric disturbances is inhibited. At high latitudes, the more vertical magnetic field promotes strong magnetospheric-ionospheric coupling.

From a variety of experimental observations, it is known that the high-latitude ionosphere, from the auroral zone into the polar cap, is a nonequilibrium medium containing structure with scale sizes ranging from hundreds of kilometers to centimeters. The high-latitude ionosphere is profoundly affected by energy sources of magnetospheric origin. Several structure source mechanisms have been proposed:[1-3] particle precipitation from the magnetosphere, bulk plasma processes, plasma instability mechanisms, and neutral atmosphere dynamics. The relative importance of each mechanism undoubtedly depends on scale size and geographic location with respect to the impressed magnetospheric boundaries.

In studying high-latitude structure and irregularities, it is possible to witness, in the readily accessible near-space environment, the evolution of structure in a magnetized, partially ionized plasma that is subject to strong driving forces. And although the high-latitude situation is substantially more complicated than its equatorial counterpart, there are several straightforward directions in which to proceed in order to make substantive progress.

Important questions include:

1. When and where in the high-latitude ionosphere is plasma structure produced?
2. What are the scale, size, spectral distributions, and associated causal mechanisms?
3. What is the role of plasma transport and what is the structure lifetime?
4. What are the roles of magnetospheric dynamics and the background ionosphere?
5. How do plasma processes couple between altitude regimes?

MAGNETOSPHERIC SOURCES

Plasma in the high-latitude ionosphere is created primarily by solar ultraviolet radiation and by precipitating electrons. The flux of precipitating ions is

significantly less than that of the electrons, and their contributions to ionospheric plasma will not be considered here. The plasma produced by the extreme ultraviolet solar radiation varies smoothly in density, while that from precipitating electrons may be highly structured. There are many other possible sources of structure, reflecting a variety of plasma processes including instabilities driven by free energy sources such as field-aligned currents and magnetospheric electric fields. Once created, these structures may be transported by impressed magnetospheric electric fields. They undergo further evolution through bifurcation and cascading processes that lead to ultimate dissipation. The purpose of this section is to explore the patterns of electron precipitation, convective electric fields, field-aligned currents, and the ionospheric density structure in the context of structure source mechanisms.[1]

Particle Precipitation

It is generally accepted[1] that precipitating electrons are a principal source of ionization structuring at high latitudes. In this, they play a dual role. First, they are free energy sources for certain plasma instabilities. Second, because magnetospheric electrons are inherently structured, so too is the ionization they create. Electron precipitation at high latitudes is variable in its energy characteristics and in its geographic distribution. High-latitude precipitation is traditionally divided into three distinct regions: the auroral oval, the dayside cusp, and the polar cap.

There are two characteristic types of electron precipitation in the auroral oval. Electrons from the central plasma sheet precipitate into the diffuse aurora. These electrons typically have energies of a few kiloelectronvolts and are isotropically distributed in pitch angle over the downcoming hemisphere. Although structured precipitation, e.g., that associated with inverted-V structures[4] and discrete auroral arcs, may be found in this region, electron precipitation is usually smoothly varying and produces diffuse auroral emission patterns. Precipitation near the high-latitude boundary of the auroral oval, sometimes referred to as boundary plasma-sheet precipitation, is characterized by discrete structures. In quiet times, the mean thermal energy of boundary plasma-sheet electrons is typically a few hundred electronvolts. In discrete arc and inverted-V events, these electrons are accelerated through field-aligned potential drops of several kiloelectronvolts. During substorm periods, the average energy of boundary plasma-sheet electrons increases dramatically.

Precipitation into the dayside cusp can be highly structured. The cusp is a spatially limited region that extends in altitude out to the dayside magnetopause, where magnetosheath plasma gains direct access to the magnetosphere. The intersection of the cusp with the polar ionosphere generally lies between 75° and 80° magnetic latitude in the noon sector. Consistent with their magnetosheath origin, electrons detected in the cusp region always have very soft spectra. In most cases, cusp electrons have Maxwellian energy distributions with mean thermal energies less than 10 electronvolts and essentially no electrons with energies greater than 1 kiloelectronvolt. Again, it is expected that such electrons would produce ionization in the F-region ionosphere. Except when the cusp region is in darkness, these electrons will have little effect on height-integrated conductivities since extreme ultraviolet solar radiation is the dominant ionization source in the E region where the conductivities peak.

Relatively uniform low-energy electron fluxes into the polar cap have been characterized[5] as "polar rain." This type of precipitation can fill the entire polar cap. These particles have mean thermal energies of 100 electronvolts and are isotropically distributed in pitch angle outside the atmospheric loss cone. The energy fluxes carried by these electrons range from 10^{-10} to 10^{-3} erg per square centimeter per second, two or three orders of magnitude less than typical energy fluxes in the auroral oval. The similarity of the spectral slope of these particles to that of those measured in the dayside cusp suggests that polar rain electrons are of direct magnetosheath origin.

Embedded within the broader regions of polar rain are occasional enhanced fluxes of precipitating electrons. These electrons have mean thermal energies of 100 electronvolts but have undergone field-aligned accelerations that range from several tens of volts to approximately one kilovolt. Electrons that undergo accelerations of 1 kiloelectronvolt are thought to be responsible for visible, sun-aligned arcs into the polar cap. Those having undergone lesser accelerations are thought to be responsible for the subvisual F-region aurora.[6] It should be noted that the enhanced polar cap fluxes associated with polar showers are most frequently observed during periods of northward interplanetary magnetic field.

Electric Fields

When the interplanetary magnetic field has a southward component, there exists a large-scale convection electric field that transports the plasma through the auroral oval toward local noon and toward midnight within the polar cap. The overall character of the pattern is variable and influenced by the solar ecliptic y component of the interplanetary magnetic field.[7] This electric field may play a role of producing and redistributing plasma structure throughout the entire high-latitude ionosphere.

Measurements of ion drift velocities and electric fields show that they possess considerable structure superimposed on the large-scale sunward and antisunward convection. In both morning and evening sides of the high-latitude region, the relatively smooth transition from corotation to significant velocities directed toward the sun begins at the equatorial edge of the diffuse auroral precipitation. This equatorward transition of the diffuse auroral zone is quite pronounced and commonly changes in magnitude by a factor of 2 over spatial scales less than 100 km. In some cases, changes of an order of magnitude at scale sizes ranging from several kilometers to several hundred meters

can be observed. Perhaps the most important point to be emphasized, however, is that very little structure in the direction of the electric field can be expected in this region.

The transition from sunward to antisunward convection produces a natural reversal in the direction of the electric field. The reversal takes place over distances of 10 to 200 km and is associated with discrete precipitation events on the dusk side. Examination of the electric field within this region reveals, however, that a single, well-defined reversal often does not exist. Rather, structures exist at scale sizes down to several hundred meters. Unlike the diffuse auroral zone, these structures contain significant changes in electric field direction, as well as magnitude, and are therefore a region where strong velocity shears exist.

Electric field structure is not limited simply to the auroral zone but also exists in the cusp region and the polar cap. Data from the DE-2 satellite indicate that structure in the cusp electric field exists at scale lengths from 1 km down to 1 meter. This structure exists both in magnitude and direction, although changes in direction of less than $45°$ are generally seen. During periods of a southward interplanetary magnetic field, the large-scale electric field in the summer polar cap varies principally in magnitude. A wide range of spatial scales is again observed, but the amplitude of the structure is generally smaller than that observed in the auroral zones. The most significant changes taking place, when the interplanetary magnetic field has a northward component, are the frequent disappearances of a large-scale plasma-circulation pattern. Under these conditions, the highest latitudes show an increase in structure at spatial scales of 1 km and greater, and structures displaying changes in both magnitude and direction can be expected throughout the high-latitude ionosphere. At shorter wavelengths, structures are similar to those found in the auroral oval.

Field-Aligned Currents

Structure in the electric fields, magnetic field, and precipitating particles is electrodynamically coupled. Large-scale field-aligned currents in the auroral oval are electrodynamically tied to the plasma convection. Their general patterns, including the delineating of region 1 and region 2 currents and their general behavior, are well known.[8] Of particular interest to studies of ionospheric structure is the fine structure in the currents. Currents in both directions that vary over short spatial scales occur both in regions 1 and 2. If the ionospheric conductivity is solar controlled, then changes in field-aligned currents closely mirror the changes in the electric field (**E**). Field-aligned currents on the order of 100 amperes per square meter can change over scale sizes of a few kilometers or less. These can be drivers for instabilities. The principal carriers of the upward currents are the precipitating electrons. Downward currents are presumed to be carried by upward thermal electron flows.

IONOSPHERIC SOURCES

Ionospheric plasma instabilities have been proposed to be a source of high-latitude ionospheric structure and irregularities. It is logical to consider plasma processes in discussing high-latitude ionospheric irregularities since several sources of free energy are available to drive various plasma instabilities. Examples of these sources include density gradients, electric fields, neutral winds, velocity shears, and currents both parallel and perpendicular to the geomagnetic field. Both plasma macroinstabilities, which are fluid-like and operate on scale sizes $\lambda \gg a_i$ (with a_i being the ion gyroradius), and plasma microinstabilities ($\lambda < a_i$) have been invoked to account for high-latitude ionospheric structure. Because of the diverse scale sizes associated with ionospheric structure, theoretical studies are usually broken into two parts: macrophenomena and microphenomena. We define "micro" to denote fluctuations with wavenumbers satisfying $ka_i > 1$. In this section, we discuss both the macroinstability and microinstability regimes.

It is well known that under certain conditions convecting ionospheric plasma clouds are unstable and can produce plasma structure through the $\mathbf{E} \times \mathbf{B}$ gradient-drift plasma instability. This convective instability[9] has a nonlinear evolution resembling the classical Rayleigh-Taylor instability in which a heavy fluid is supported by a lighter fluid. The basic $\mathbf{E} \times \mathbf{B}$ instability mechanism can be understood by noting Fig. 1. The ambient background electric field $\mathbf{E}_0$ is in the $-x$ direction, the ambient magnetic field $\mathbf{B}_0$ is in the z direction, and the background density gradient points in the y direction. Let the density be perturbed by a small amplitude sinusoidal perturbation with wavenumber k parallel to $\mathbf{E}_0$. In the F region, the ions drift to the left in the Pedersen direction relative to the electrons. This gives rise to positive and negative space charges that in turn cause small-scale electric fields $\mathbf{E}'$ alternating in direction as shown. The corresponding $\mathbf{E}' \times \mathbf{B}_0$ drifts will then convect depleted regions upward (toward increasing density) and enhanced regions downward (toward decreasing density) with the result that they both appear to grow relative to the background density gradient — an unstable situation. The presence of the highly conducting auroral E layer may reduce $\mathbf{E}'$ and hence the growth rate by the ratio of the E- and F-region height-integrated Pedersen conductivities. This reduction factor can be as high as 100 for typical auroral conditions.[10,11]

Keskinen and Ossakow[12] have proposed that the $\mathbf{E} \times \mathbf{B}$ gradient drift instability is a source of high-latitude ionospheric structure. Using both analytical and numerical simulation techniques, they have studied the linear stability and nonlinear evolution of large-scale convecting plasma enhancements in the auroral F-region ionosphere. Their results indicate that convecting diffuse auroral plasma enhancements can be driven unstable through the $\mathbf{E} \times \mathbf{B}$ instability, generating plasma density and electric field structure with
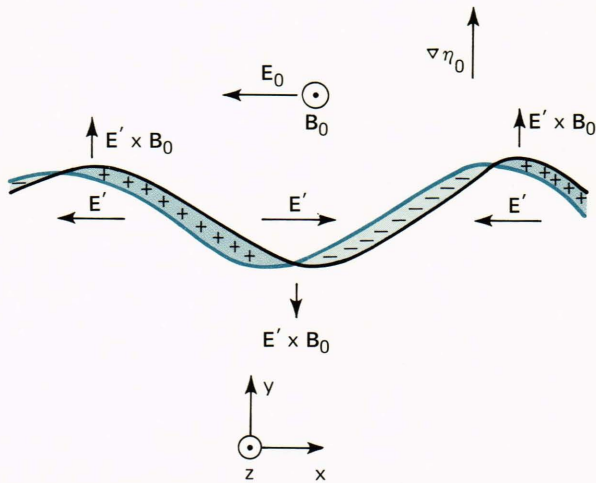
Figure 1 — Physical mechanism of the **E** × **B** gradient drift instability.

sizes of tens of kilometers to tens of meters. The irregularities take the form of striation-like structures, elongated in the north-south direction for equatorward convection, that can form on the order of half an hour in the absence of the auroral E layer. These theoretical results are not inconsistent with recent experimental observations, using the Chatanika radar, that indicate large neutral wind velocities (**E** × **B** instability) and finger-like structures collocated with large-scale convecting plasma enhancements.

In addition, Keskinen and Ossakow[12] found that the large-scale irregularities (fingers) can cascade to small-scale structures through nonlinear mode coupling. The spatial power spectra of the irregularities in simulations can be well represented by power laws. This process of finger formation, elongation, and steepening is almost self-similar in character with similar morphologies and power spectra for scale sizes between 1 km and 100 meters. Some observational evidence indicates that these plasma enhancements are probably subjected to ambient auroral convection patterns. As a result, the enhancements could be a major source of F-region ionospheric structure throughout the auroral zone and region.[13]

Another plasma instability that has been invoked[14] to explain aspects of high-latitude ionospheric structure is the current convective instability, which results from the coupling of a magnetic field-aligned current and a plasma density gradient transverse to the magnetic field. Its nonlinear evolution resembles that of the **E** × **B** instability in the above paragraphs. A maximum linear growth rate was derived that favored creation of this plasma instability at an altitude of 400 km over, say, 200 km. The instability is fluid-like in nature and so could account for the long wavelength diffuse auroral irregularities directly, as can the **E** × **B** instability.

Still another source of plasma-free energy that could directly excite large-scale irregularities in high-latitude F-region ionosphere is the velocity-sheared plasma flows,[15] e.g., near auroral arcs. For unstable velocity-sheared plasma flows perpendicular to a magnetic field, the growth is nonlocal and maximizes for irregularity wavenumbers k such that $kL_v < 1$, where L_v is the scale length of the velocity shear gradient. A local instability ($kL_v > 1$) can operate for velocity-sheared plasma flow parallel to a magnetic field.

There are several plasma instabilities that can excite very small, meter-sized irregularities in the high-latitude ionosphere. The universal drift instability, ion cyclotron instability, and the two-stream instability are several obvious candidates.[15]

AN EMERGING THEORETICAL PICTURE

A general emerging picture of the birth, growth, and decay of high-latitude ionospheric structures is developing.[1-3] At scales greater than about 50 km, structure is believed to be primarily due to that identified with incoming particle precipitation patterns. This is especially true in the E region and lower F region, where electrons with energies greater than 1000 electronvolts produce ionization with lifetimes of a few minutes. Electrons with energies of hundreds of electronvolts produce upper F-region ionization enhancements that can have lifetimes of hours, allowing significant redistribution within the high-latitude region. This "initial" large-scale structure is subject to a variety of free energy sources to drive various plasma macroinstabilities that, in turn, can populate the smaller scale regimes, both directly and indirectly, through wave-wave interaction and cascading. Further structuring can be quenched by diffusive-like processes. Plasma microinstabilities can provide wave-particle diffusion, which in turn affects the decay of large-scale structures. These instabilities must operate on short time scales when compared to the plasma lifetimes. Moreover, the time scales for growth and dissipation of the structure may vary throughout the convecting lifetime.

In the scale-size regime greater than about 100 km, high-latitude ionospheric structure has been identified principally by in situ satellite observations. Virtually no theoretical arguments exist that specifically treat the structure and scale sizes in this regime. One exception would be the excitation of the 100-km-wavelength thermal gravity waves that couple to the ambient plasma and produce structure through collisional effects.

In the 1 to 100 km scale-size regime, high-latitude structure has been identified using both in situ and ground-based observations. Irregularities in this scale-size regime can be caused by structured particle precipitation, ion chemistry, and plasma instabilities. The mapping between magnetospheric and ionospheric structure may be important but has not been assessed. It is known the D- and E-region auroral patches that appear in the equatorward part and morning sector of the auroral oval have irregular shapes and typical sizes from 10 to 50 km. The shape of the patches is coherent for time scales of tens of minutes.

The inverted-V structures[4] have long been identified with the discrete auroral forms because the precipitation occurs along a field line poleward of the

trapped fluxes in the regions where the discrete aurora is commonly observed. Lin and Hoffman[16] have made a systematic study of inverted-V events and report typical latitudinal widths of about 50 km. These dimensions are much larger than typical discrete arc widths and refer more to auroral bands. Theoretically, several mechanisms, e.g., anomalous resistivity, double layers, and magnetic-mirror electric fields, have been invoked to explain inverted V's, but little theoretical work has been published that addresses their spatial structure. In the auroral F region, ground-based and in situ observations have shown plasma structure in this scale-size regime. These plasma structures have transverse scale sizes comparable to inverted-V events and follow ambient auroral convection patterns. No theoretical work has been performed that can predict their scale sizes, but they have been shown to be unstable to convective plasma macroinstabilities.

Information about wavelengths shorter than 10 meters primarily comes from radar backscatter and satellite electric field observations. In the auroral E region, there is good agreement between Farley-Buneman[17] and $E \times B$ instability theory and experimental observations. In the high-latitude F region, very little data in this short wavelength regime have been taken to date using backscatter radar owing to the vertical field line geometry.

Structure in the plasma density and the electric field may produce structure in the other plasma parameters. For example, the electron cooling rate with ions is a strong function of the plasma density. Thus, at high latitudes, a uniform heat input may result in electron temperature structure associated with structure in the plasma density. Also, structured particle precipitation fluxes will directly produce structure in the electron temperature. This, in turn, is manifested in a structured plasma scale height. In addition, significant frictional heating of F-region ions occurs when their motion relative to the much denser neutral atmosphere exceeds 500 meters/second. This high relative motion also significantly increases the ion chemical loss rate.

Sun-aligned F-region ridges of high-density plasma in the polar cap have recently been discovered. They are produced by long exposure to fluxes of soft electron precipitation and have structure ranging on the order of 100 km to tens of meters. In the ridge where plasma densities on the order of 10^6 per cubic centimeter exist, ion-neutral momentum transfer accelerates the F-region neutral atmosphere to near the plasma velocity in a fraction of an hour. Large-scale regions of plasma structures with this density should thus produce comparably large-scale structure in the velocity of the neutral atmosphere.

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