Remote Sensing the Earth's Plasmasphere

D.L. Carpenter

1. Introduction

The plasmasphere is a doughnut-shaped plasma cloud that surrounds the Earth to an equatorial distance of several R_E (see, for example, [1], and references cited therein). Consisting primarily of cool (~1 eV) H^+ ions and electrons, supplemented by smaller populations of He^+ and O^+, it acts in part as a high-altitude extension of the Earth's regular (<1000 km altitude) ionosphere. As an element of the Earth's space weather system, it is subject to substantial changes during storm-like disturbances in space induced by solar activity. Figure 1 shows the location of the plasmasphere with respect to other features of the Earth's space environment, in cartoon fashion.

As is often the case with experimental work in space, the initial detection and description of the plasmasphere were accomplished without being predicted theoretically. Remarkably, these discoveries occurred through remote sensing from the ground, before the advent of the first high-altitude Earth-orbiting satellites.

In the early 1950s, Owen Storey, a graduate student at Cambridge University, investigated the puzzling phenomenon of whistlers, dispersed audio-range signals from lightning. In a work of profound importance for space physics, Storey [2] showed for the first time that whistler signals followed long paths in space, extending from one hemisphere to the other. He was able to demonstrate that the electron density at ~12,000 km altitude over the Earth's equator was ~400 el/cc, orders of magnitude higher than could be expected based upon contemporary understanding of the Earth's ionosphere and its probable extent above its peak at about 300 km altitude. These results had immediate impact: Within a year, J. Dungey [3], speaking at a 1954 conference on the physics of the ionosphere, speculated that charge exchange between H^+ and O^+ is important in the upper atmosphere, and stated in reference to Storey's work that "the many attractive features of his interpretation make

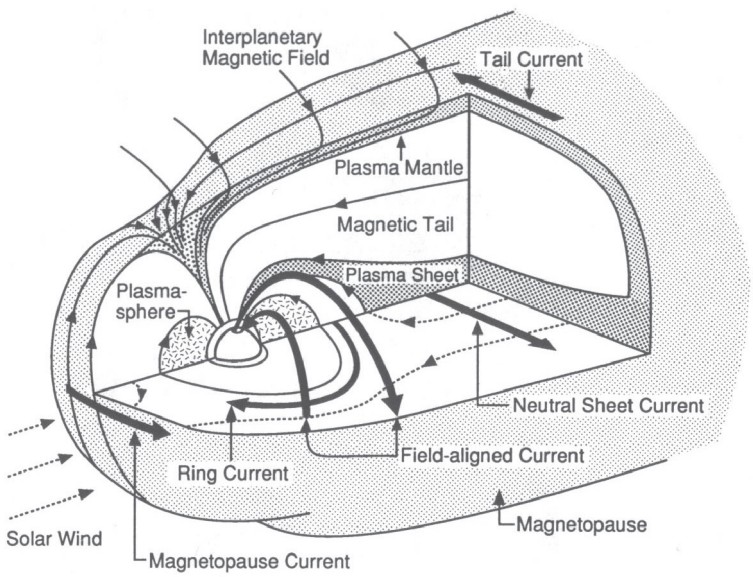

Figure 1. A diagram, from [129], of the space environment of the Earth, showing the location of the plasmasphere within the larger comet-like "magnetosphere," or region dominated by the Earth's magnetic field. Also shown are various important current systems and the interplanetary magnetic field.

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Editors Note: This paper is one of the invited *Reviews of Radio Science*, from Commission H.

it [Storey's estimate of electron density at 12,000 km] reasonably certain."

In the early 1960s, thanks to further advances in understanding of their potential as natural probes of the Earth's plasma envelope, whistlers were used to show that the dense plasma region first detected by Storey has a geomagnetic-field-aligned boundary. This boundary was eventually called the plasmapause, the region at which the density level drops by about one order of magnitude [4]. Such a drop, also detected by ion traps aboard the Soviet lunar rockets in 1959 [5], was not expected according to contemporaneous ideas about the behavior of a high-altitude plasma in gravitational equilibrium [1]. Some had argued that plasma in the outer magnetosphere, under the influence of the solar wind, does not undergo bulk motions on trajectories that encircle the Earth [6]. However, there were essentially no predictions that the density in that outer region would be substantially lower than in the inner, approximately co-rotating region (except for reductions attributable to differences in flux-tube volume).

Remote sensing by whistlers thus led to new paradigms: (1) a light ion gas, the protonosphere, floats on the heavier ion gas of the regular, low-altitude ionosphere (see, for example, [7]); (2) an outer magnetospheric circulation pattern, driven by the solar wind, is configured so as to prevent a buildup of ionization along high-latitude field lines. Such a buildup might otherwise occur were there substantially longer periods of plasma interchange with the underlying ionosphere in those field line regions [8-11].

From its initial detection in 1953 to the present day, the plasmasphere has remained an attractive yet challenging target for remote sensing. Huge in size, of the order of 100 times the volume of the Earth, it regularly experiences complex cycles of erosion and replenishment during storm-like space weather events (see, for example, [12]). As an ever-changing plasma-wave propagation environment, it imposes corresponding changes on the conditions under which resonant interactions can occur between various wave modes and the hot, tenuous plasmas of the Earth's radiation belts. Through wave-induced particle scattering, such interactions give rise to particle precipitation into the Earth's upper atmosphere, and thus play a role in the loss of energetic particles injected into the magnetosphere during storm events (see later section). Wave-induced particle precipitation is known to affect the properties of the ionosphere as a wave propagation medium (see below). Such precipitation, varying in intensity and precipitating particle energy from inside to outside the plasmapause [13], may possibly affect the NO chemistry of the ionosphere (see, for example, [14]). Inward displacements of the plasmapause and steepening of its density profile represent conditions in which the potential of a satellite and its detectors can change rapidly, a situation that can complicate particle measurements but which also provides a means of sensing the plasmapause location in situ [15, 16].

Over the years, a variety of remote sensing methods have been developed and applied to the plasmasphere. Among these are: (1) the whistler-mode method of studying plasma-density structure and its variations with time, (2) the whistler-mode method of tracking plasma bulk motions, (3) the study of wave-particle energy and momentum exchange by injection of whistler-mode waves from the ground as well as by means of instruments for detection of wave-induced particle precipitation into the ionosphere. In the last decade, in an ongoing period of revived interest in plasmasphere studies, these methods have been supplemented by: (4) ultra-low-frequency (ULF) wave methods of determining mass density, (5) incoherent scatter and TEC measurements of plasmaspheric effects as they are manifested in the ionosphere, (6) EUV photon imaging of the plasmasphere by satellite measurements of scattered 30.4 nm sunlight from He^+ ions, (7) radio sounding of the plasmasphere along a high-altitude orbit. Without attempting to comprehensively review each topic, we now briefly describe these remote-sensing methods, and note some of the problems to which they have been applied. We also mention a number of the outstanding problems that remain.

2. The Whistler Propagation Method

2.1 Studies of Plasma Density Structure

The whistler method is illustrated schematically in Figure 2. It begins with a lightning discharge, shown in this case as occurring in the Northern Hemisphere. The impulsive very-low-frequency radiation from the lightning spreads in the Earth-ionosphere cavity. A fraction of this radiation penetrates the ionosphere, and at some locations becomes trapped in geomagnetic-field-aligned ducts, propagating therein to the conjugate hemisphere. A portion of the down-coming whistler wave energy is then able to penetrate the highly refracting ionosphere, after which the waves spread in the Earth-ionosphere waveguide and may be detected by ground receivers.

The remote-sensing power of a ducted whistler (see, for example, [17-21]) comes from the fact that its group velocity at any point is approximately proportional to the 1/2 power of the geomagnetic field strength. The observed delay-time-versus-frequency properties of a whistler are thus heavily weighted by the plasma environment along the most remote, near-equatorial, portion of its path, where variations in the plasma parameters per unit distance along the field lines are minimal. As a result, whistlers have been found to provide measures of total electron content within flux tubes of propagation, as well as measures of electron density near the magnetic equator that are relatively insensitive to the functional form of the distribution of plasma along the field lines used in the calculations [22, 23].

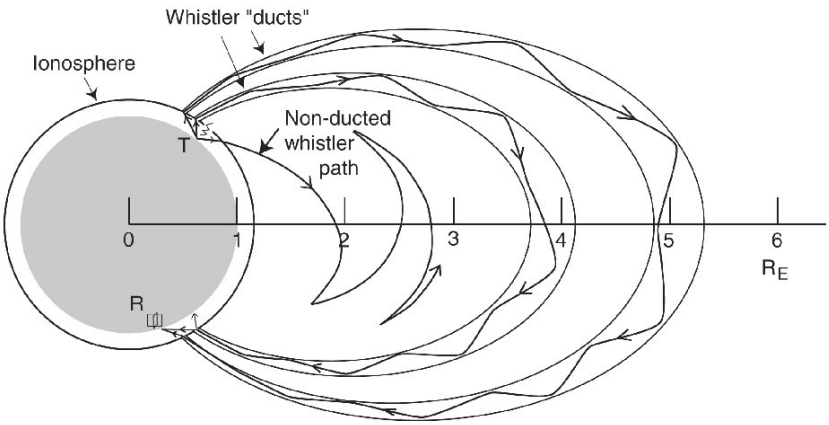

Figure 2. A meridian cross section of the Earth, showing in cartoon fashion the paths by which impulsive very-low-frequency energy from lightning, or signals from a ground transmitter (T), can propagate from hemisphere to hemisphere along discrete geomagnetic-field-aligned paths. The paths are believed to involve field-aligned density enhancements, which trap the waves and allow them to propagate with low loss in a manner analogous to that of waves trapped in optical fibers. A so-called "non-ducted" whistler path is also shown, in which the up-going wave energy, after penetrating the ionosphere, does not become trapped within a duct.

Whistlers regularly exhibit multiple discrete components, and are used to obtain information on equatorial electron density at multiple locations, for example near 4 R_E and 5 R_E geocentric distances in the simplified example of Figure 2.

Whistlers provided much of the early information on the global shape of the plasmasphere, on its equatorial density profile, and on the fact that it undergoes cycles of erosion and recovery during magnetically disturbed periods. In particular, discovery of a bulge-like extension in plasmasphere radius in the dusk sector [24] stimulated early efforts to interpret the shape of the plasmasphere in terms of the interplay between the motion of the plasma imposed by the Earth's rotation and the generally sunward flow in the middle magnetosphere driven by the solar wind as it impinges upon the magnetosphere [9, 10].

As data were accumulated over time and at many locations, it became possible to identify major temporal variations in the density of the plasmasphere, ranging in periods from hours to 11 years [25]. One of the more pronounced and, for many years, least well understood of these is an annual variation, with a maximum in December and a peak amplitude (~2:1) in the vicinity of the 75º W meridian [26]. The inherent difficulty in understanding the interplay between the comparatively rapidly changing ionosphere and the overlying but more slowly varying plasmasphere is illustrated by the fact that mechanisms that could explain the annual variation have been found both in the properties of the ionosphere [26] and in plasmasphere thermal structure [27].

Whistlers also made possible study of the interchange of plasma between the ionosphere and overlying plasmasphere, providing measures of the rate at which upward fluxes from the ionosphere refill depleted overlying regions [28], and clarifying the role of the plasmasphere as a reservoir for the decaying night-time ionosphere [29].

2.2 Tracking Plasma Bulk Motions

In the 1960s, it was realized that the radial, or cross-L, motions of discrete whistler paths could be tracked through measurements of corresponding changes in the

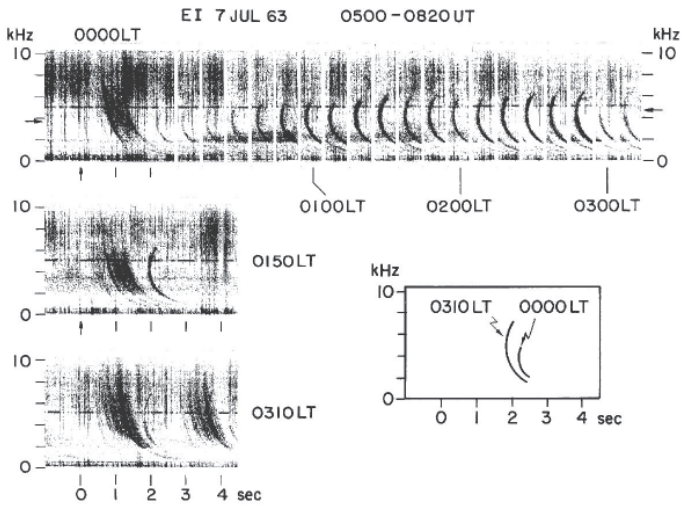

Figure 3. An illustration of the gradual changes in the frequency-time spectra of an individual whistler component as its discrete field-line path underwent bulk motions in a direction transverse to the geomagnetic field (from [24]). The recordings were made at Eights Station, Antarctica, on July 7, 1963.

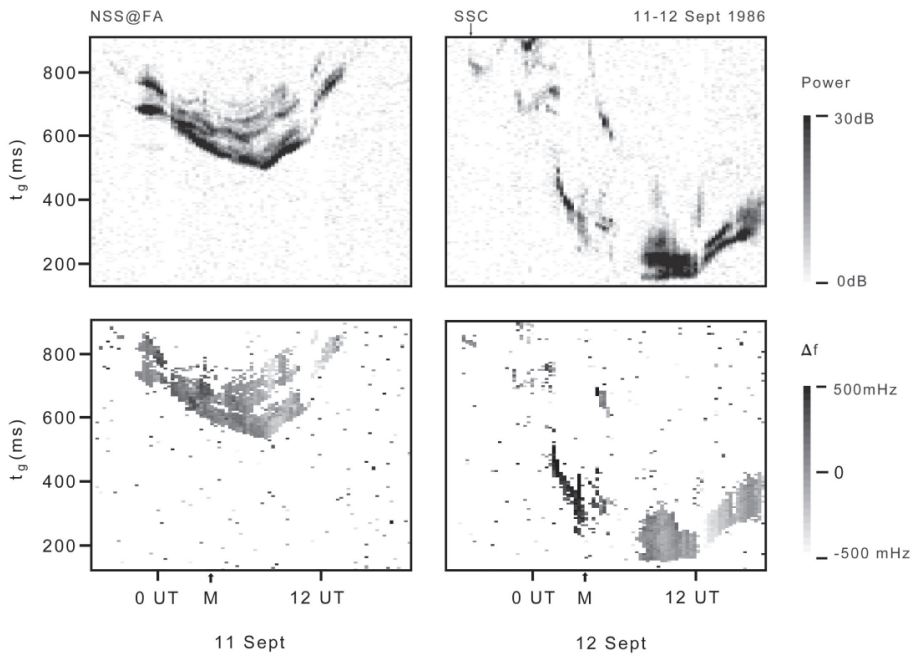

Figure 4. Examples of Doppler receiver data for September 11-12, 1986, showing nighttime changes in the group delay (above) and Doppler shift (below) of signals propagating from the NSS transmitter in the eastern US to a receiver in the Southern Hemisphere at Faraday Station, Antarctica (from [35]). The left panels show quiet-day behavior; the right panels show behavior following a sudden storm commencement (SSC).

travel time and curvature of the associated whistlers [24, 30, 31]. This would allow estimates of the azimuthal, or east-west, component of the large-scale magnetospheric electric field associated with the radial bulk motions. Figure 3 shows an example of gradual changes in the frequency-versus-time spectra of whistlers recorded during a three-hour night-time period [24]. At the left from top to bottom are three whistlers, recorded at 0000 MLT, 0150 MLT, and 0310 MLT, respectively. At the lower right is a tracing of the dispersion curve of one of the whistler components as it appeared at the beginning and at the end of this three-hour period. Along the top panel is a series of spectral segments, showing the traced component at roughly 10 minute intervals; its field-line path was found to have drifted inward through $\sim 0.3 R_E$ during the time displayed.

Extended-time series of whistlers recorded near the 75° W meridian in Antarctica provided the first evidence of enhanced sunward drifts in the outer plasmasphere on the night side of the Earth during substorms [30], an effect that had been predicted by early theoretical work on magnetospheric convection (see, for example, [6]). Eventually it became possible to develop an empirical model of the radial component of substorm-associated drifts [32]. Also studied was a distinctive pattern of quiet-day radial drifts in the plasmasphere, apparently driven by neutral winds of thermal origin that flow in the ionosphere and give rise to the quiet-day SQ current system [33].

Fixed-frequency whistler-mode signals from communication transmitters propagating on magnetospheric paths presented an exceptional remote-sensing opportunity. Through a combination of measurements of group delay and Doppler shift, it became possible during drift events to separately identify and assess the effects of changing path length and of plasma interchange with the underlying ionosphere [34]. Figure 4 shows an example of Doppler receiver data obtained on two successive nights, one calm and the other disturbed by a sudden storm commencement [35, 36]. Local midnight is indicated by an "M" at the bottom. A major part of the quiet-day changes (left) is attributed to interchange fluxes with the ionosphere (decay at night followed by morning-side replenishment). The larger excursions on the second night reflect the occurrence of inward bulk motions of the plasma during episodes of enhanced convection electric fields.

In the 1980s, digital processing was applied to original tape-recorded data of fixed-frequency several-kHz signals from an experimental transmitter at Siple, Antarctica [37]. The signals had propagated along paths near $L = 4$ to a ground station in Canada. From comparisons of the received signal phase with the phase of a stable reference, it was found possible to estimate the drift rate of a signal path with a time resolution of seconds, in comparison to the order of minutes or tens of minutes required through group-delay measurements of whistlers.

2.3. Outstanding Problems in the Area of Passive Whistler Mode Probing

It is a curious fact that although remote sensing of the magnetosphere depends upon propagation guided by field-aligned density structures or ducts [38], very little specific information is available about the structures, including their origin and distributions in space. The situation is illustrated by findings that a single ducted whistler can contain several hyperfine elements [39, 40], and awareness that this could be interpreted either in terms of spatial electron-density

fluctuations, or possibly in terms of the excitation of multiple propagation modes within a duct [41]. There is a need to bring theory and observations closer together on this subject, bearing in mind that the literature contains a number of papers about instabilities or electric-field configurations that may give rise to density structure within and beyond the plasmasphere [42, 43, 1]. Through both modeling and experimental work, more needs to be learned about the excitation of ducts by up-going whistler-mode waves, about propagation within ducts, and about the conditions of de-trapping of ducted waves in the topside ionosphere [44].

Whistler-mode probing, both by whistlers and transmitter signals, continues to have great potential for remote sensing of plasma motions, time variations, and density structures. Past work, especially with whistlers, has been limited in scope by the laborious nature of the pattern-recognition methods used. Future work, capable of analyzing large quantities of data and at times based upon controlled wave injection, could fill many gaps in our knowledge, as well as provide routine "space weather" information on key geophysical quantities such as equatorial profile levels and plasmapause radius. One of the challenges in this new work would be to further develop and apply tools for automatic detection and analysis of whistlers, along lines discussed by Hamar and Lichtenberger [45]. Much can be accomplished through applying modern digital signal-processing methods to libraries of tape-recorded data acquired during past measurement campaigns in regions of exceptionally high activity.

Phase measurements of whistler-mode signals can apparently be used to detect the equatorial component of ULF field-line perturbations. Paschal et al. [46], using several-kHz signals from the experimental Jupiter transmitter at Siple, Antarctica ($L \sim 4.3$), showed how this method could be used to detect ULF activity along a particular L shell, the L value being determined from dispersion measurements on multi-frequency components of the signals. The possibilities of this method, which would not be restricted to the dayside of the Earth, have yet to be explored.

3. Remote Sensing of Hot Plasma Effects

3.1 Whistler-Mode Wave-Injection Experiments

Early studies showed that whistler-mode signals that emerge from the magnetosphere and are incident on ground antennas can carry both an imprint of the cold component of the magnetospheric plasma through which they have propagated, as well as evidence of interactions with the hot electrons of the Earth's radiation belts [47-51]. The cold dense plasma provides a slow-wave structure that controls the velocity-versus-frequency characteristics of the waves. The radiation-belt electrons can exchange energy and/or momentum with the waves through cyclotron or Landau resonance interactions along the geomagnetic field line paths, and hence influence the amplitude spectra of the waves (see, for example, [52]).

It was found that both whistlers and fixed-frequency whistler-mode signals from transmitters can trigger emissions at new frequencies [49, 53]. The transmitter

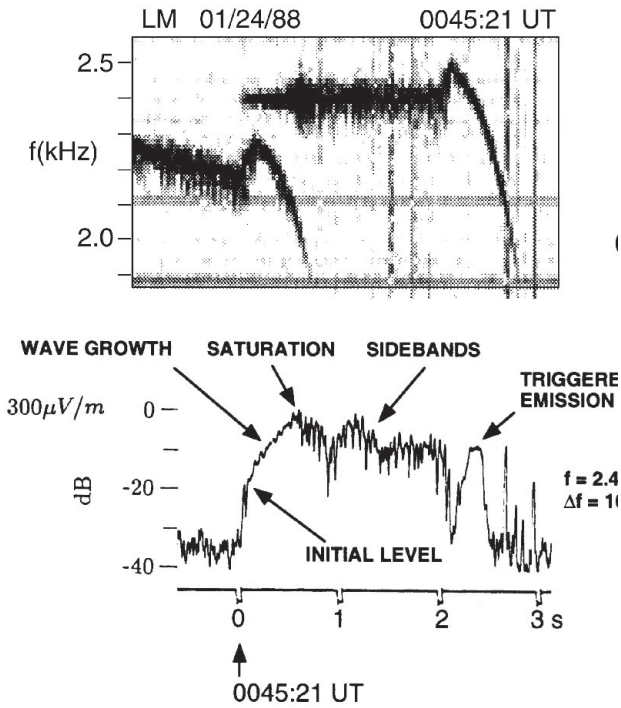

Figure 5. A frequency-time spectrogram and associated amplitude record illustrating the occurrence of the Coherent Wave Instability (adapted from [58]). The recording was made at Lake Mistissini, Canada, on January 24, 1988, during reception of signals propagating through the magnetosphere from Siple Station, Antarctica.

signals were of particular interest; they showed evidence of pulse-length-dependent emission triggering, indicative of fast temporal growth of the triggering signal [50]. Such findings became the impetus for controlled whistler-mode wave-injection experiments initiated in the late 1960s and early 1970s. A number of such experiments were successfully conducted on a campaign basis between Alaska and New Zealand, using a transportable VLF source and a balloon-borne antenna [54]. The most extensive work was carried out on a regular basis from 1973 to 1988 between Siple Station, Antarctica, and conjugate stations in Quebec, Canada [55]. In this case, it had been speculated that extensive signal processing would be needed for detection of magnetospherically propagating signals near L = 4 from such a weak source, radiating at most a few kilowatts from a 21-km or 42-km-long horizontal dipole over a 2-km-thick Antarctic ice sheet. Instead, signals were regularly received at levels tens of dB above the background noise, showing evidence of temporal wave growth of the order of 30 dB, and growth rates in the range 20 to 250 dB/sec [56].

Over time, the major elements in what became known as the coherent wave instability (CWI) were studied under various conditions of transmitter frequency and pulse length [57]. Figure 5, from [58], shows a spectrogram of two Siple signals received in Canada: a descending-frequency ramp (first part not shown) and a two-second fixed-frequency pulse transmitted at 2400 Hz. Below is an amplitude record of the two-second pulse; it includes evidence of CWI elements such as exponential growth, saturation, sidebands, and triggering of emissions. Models of a feedback process involving an interaction region at or near the geomagnetic equator, an injected wave, and counter-streaming electrons were developed to explain what appeared to be a fundamental aspect of wave-particle interactions in near-Earth space [59, 60].

3.2 Outstanding Problems in Wave-Injection Experiments

One of many fundamental questions raised by the wave-injection experiments concerns the level of the input signal to the hypothesized high-altitude interaction region required to initiate fast temporal growth. In some theoretical treatments of the interaction problem, the input signal is assumed to be at a level sufficient to trap cyclotron-resonant electrons in the magnetic potential well of the wave (e.g., [61, 62]). In other interpretations – for which experimental evidence has been offered [63] – the input signal can be at any level above a threshold imposed by the background noise in the medium [60, 64].

3.3 Remote Sensing of Wave-Induced Particle Scattering

Scattering of radiation-belt electrons by whistler-mode waves has been a topic of interest in space physics for over 40 years [65-69]. One of the most sensitive tools for studying wave-induced precipitation of energetic electrons is the measurement of phase and amplitude perturbations on sub-ionospherically propagating VLF transmitter signals. Such perturbations, associated with secondary ionization created in the night-time ionosphere at ~80 km altitude by precipitating energetic (> 40 keV) electrons, were found to be correlated on a one-to-one basis with the propagation along the related field lines of lightning-generated whistlers (the "Trimpi Effect") [70-72]. Studies of the ionospheric perturbations and their geophysical implications were, for some time, focused on the scattering action of ducted whistlers received on the ground [73-75]. However, such studies have recently broadened to consider effects of the more general non-ducted type of whistler [76], the ray path of which may execute many crossings of the magnetospheric equator and does not usually reach the ground, as illustrated in Figure 2. Thanks to the deployment of arrays of receiving stations, it has become possible to separately identify the ionospheric perturbations induced by ducted and non-ducted waves [76, 77].

Other ground-based tools for remote study of the mechanisms of wave-induced particle scattering include X-ray detectors (see, for example, [78, 79]) and photometers [80], which have been used to investigate the effects of quasi-periodic, burst-like precipitation near the ionospheric projection of the plasmapause.

3.4 Outstanding Problems in Particle Scattering

The sub-ionosphere VLF signal work aims at understanding the contribution of both non-ducted and ducted lightning whistler waves as well as transmitter waves to losses of particles from the radiation belts. Interest continues in improved modeling of the VLF signal propagation in the presence of ionospheric perturbations, with the objective of using the observed data to infer both the ambient ionospheric profile and the size of the density perturbation [81, 82]. A longstanding question, first raised many years ago, concerns a reported widespread perturbation of the night-time lower ionosphere at plasmasphere latitudes, not apparently associated with transient whistler events, but occurring during periods of substorm activity [83, 84]. Important questions remain on the nature and geophysical significance of the strong interactions that occur between naturally occurring whistler-mode waves and energetic particles at or near the plasmasphere boundary.

4. Ultra-Low-Frequency Studies of Plasmasphere Mass Density

4.1 Experimental Method

It has long been realized that ULF pulsations detected on the ground carry information about the specific

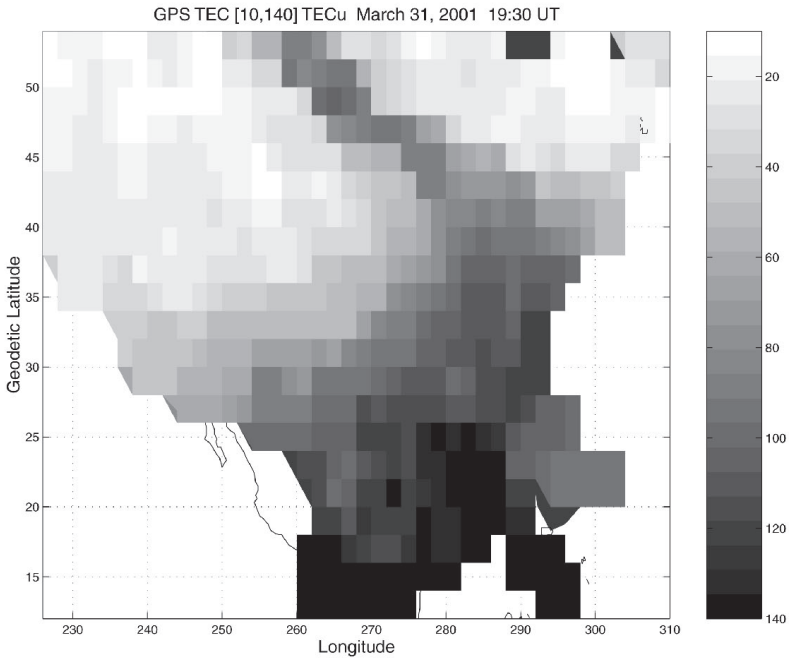

Figure 6. A map over North America of the total electron content (TEC), an integral measure of the plasma density between ground points and GPS satellites. The data were acquired on March 31, 2001, at 1930 UT, during a period of strong geomagnetic storm activity. The darker regions include an extension upward and toward the left that is interpreted as evidence of a plume of dense ionization drawn out into the afternoon sector during an erosion event in the overlying plasmasphere (from [102]).

magnetospheric regions through which the waves propagate. The idea that field-line resonance can be used to estimate the mass density at high altitudes was advanced more than three decades ago [85, 86]. The use of ULF-inferred density to study plasmaspheric properties was initiated by Webb et al. [87] and by Lanzerotti et al. [88]. In early studies, the determination of resonant frequencies suffered from contamination of the wave spectrum by the driving-wave energy. This observational difficulty was first resolved by Baransky et al. [89] with their "gradient method," using a pair of stations separated by roughly 100-200 km in latitude. This method continues in use to the present day; one seeks information on field-line resonance (FLR) frequency as a function of observing-station latitude (see, for example, [90, 91]). The phase and amplitude of the various observed ULF frequency components are determined, and through auto- and cross-correlation techniques involving spaced stations, particular ULF frequencies are identified as the eigenfrequencies associated with particular magnetic shells or L values. The value of the eigenfrequency for a particular L shell is then used to estimate the mass density along that field line at high altitudes, and from a latitudinal array of stations, a multi-point profile for the plasmasphere may be obtained, analogous to an electron-density profile obtained from a multi-component whistler. The gradient method can successfully identify eigenfrequency signatures in both the plasmasphere and the outer magnetosphere, for L values from as low as 1.5 [92] to as high as 11 [93].

Temporal changes in the profile depend upon factors such as plasmasphere erosion and refilling that affect total plasma density, and also upon changes in ion composition, which are expected to depend upon a number of factors involved in the transport of mass and energy through the magnetosphere. The ULF method is most effectively applied under daytime conditions, and continues to be developed as a geophysical tool (see, for example, [94]).

4.2 Outstanding Problems in Mass Density Measurements

Key questions that remain concern the relative abundance of heavy ions in the plasmasphere, as well as the question of plasma losses through interchange with the underlying ionosphere during magnetic storms. Study of these questions will clearly involve coordination with other experiments, as exemplified by recent comparisons among ground-based measurements of plasmasphere mass and electron density, and IMAGE satellite maps of plasmasphere He^+ content [95], supported by local measurements of electron density along IMAGE orbits.

5. Incoherent Scatter and TEC Measurements

5.1 Detection of Plasmaspheric Effects

Understanding the behavior of the ionosphere in the presence of the overlying plasmasphere has presented a major challenge to researchers over the years, in part because of the different time scales on which the two regions act in response to "space weather." For example, the

disturbance processes that establish a new plasmapause boundary may leave a clear imprint on the underlying ionosphere in the form of SAR arcs (stable auroral red arcs) [96, 97], light-ion troughs [98], and electron-temperature enhancements [99], but these coincidences are not the rule during the later phases of a disturbance/recovery cycle (see, for example, [1, 100]). However, incoherent-scatter radar data have for some time revealed plumes of enhanced ionization at ionospheric heights with plasma flow direction generally sunward [101]. Recent evidence, including measurements of total electron content (TEC) along lines of sight through the ionosphere and plasmasphere to spacecraft such as the GPS constellation, indicates that these low-altitude features are ionospheric projections of sunward-extending plumes that develop in the afternoon-dusk sector of the overlying magnetosphere as part of the plasmasphere erosion process [102]. The projections have been called SEDs, or Storm Enhanced Density(s).

The relationship between low- and high-altitude plasmas has come to light with clarity, thanks to the recent development of large-area TEC maps with a time resolution of ~15 minutes [103]. These maps have been combined with radar measurements of plasma-flow velocities in and near the SED structures, making it possible to confirm that the plumes, at least during the early phases of a disturbance, act to drain dense plasma from the main plasmasphere [102]. Figure 6 shows an example of plume effects as they have appeared on a TEC map covering a region in the Eastern US and Canada.

5.2 Outstanding Problems

It is far from clear just how faithfully ionospheric structures and motions reflect corresponding aspects of the overlying region (see, for example, [104]). Studies are needed that compare the distribution and movements of cool plasmas in the outer dayside magnetosphere with the behavior of the ionosphere. As the structure of the plasmasphere is more completely mapped on a global basis, corresponding effects in the ionosphere must be sought. One outstanding question concerns the substantially reduced density levels found within the plasmasphere in the aftermath of a period of erosion. Such losses would appear to occur via plasma interchange with the ionosphere, but corresponding ionospheric effects have yet to be clearly identified [105].

6. EUV Photon Imaging of the Plasmasphere

6.1 Observations by the EUV Instrument on the IMAGE Satellite

Arguably the most significant advance in remote sensing of the plasmasphere since the early applications of lightning whistlers is the development of wide-field cameras that map the dense plasma near the Earth by recording

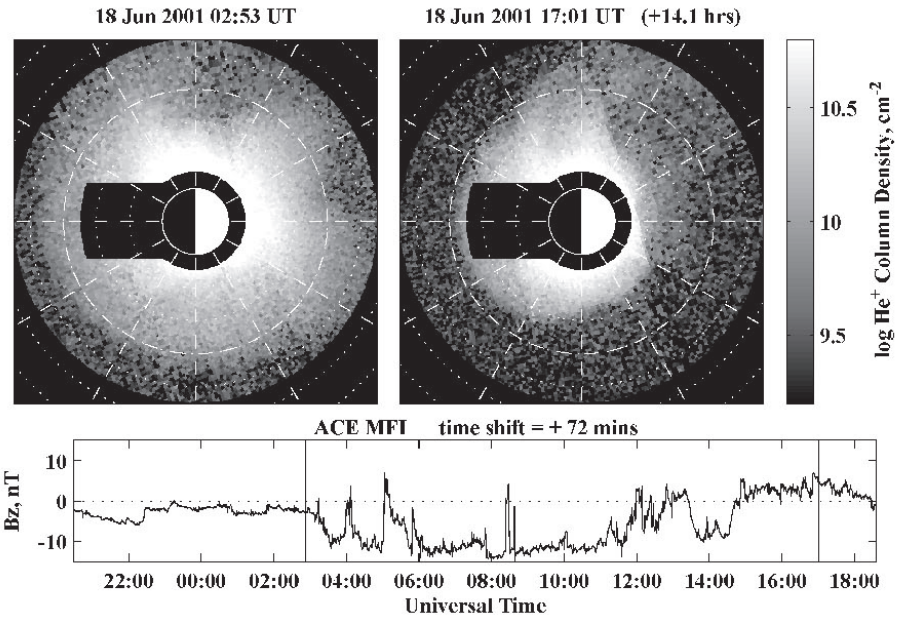

Figure 7. Global images of the Earth's plasmasphere (above) acquired by the EUV instrument on the IMAGE satellite during successive orbits on June 18, 2001, illustrating the erosion of the plasmasphere during an interval when the interplanetary Bz magnetic field component was strongly negative. The vertical lines on the magnetometer record (below) indicate the times of the EUV records, one preceding the erosion event and the other in its aftermath. The ACE magnetometer record, acquired upstream of the Earth, was shifted by 72 minutes to account for a propagation delay from spacecraft to Earth. In the EUV records, the nightside region and a region close to the Earth have been masked so as to emphasize the main body of the plasmasphere. The slanting change in brightness on the sunward side of the Earth in the right-hand panel is an artifact of the differences in view between the EUV cameras (figure courtesy of M. Spasojeviæ).

resonantly scattered 30.4 nm sunlight from the He^+ component of the plasmasphere [106]. Previously known in certain respects in a composite sense, the bulk of the entire plasmasphere suddenly leaped into view. Figure 7, upper panels, shows two 30.4 nm images of the plasmasphere acquired 14 hours apart on successive orbits by the EUV instrument on the IMAGE satellite, launched in March 21, 2000. The view is from near $8 R_E$ geocentric distance over the northern polar region. Local noon is to the right; a nightside shadow region and a high-density region near the Earth have been masked so as to emphasize the main body of the plasmasphere. Below is a magnetometer record from the ACE satellite, showing an interval of strongly negative Bz, a southward turning of the solar-wind magnetic field. Vertical lines show the times of the EUV observations above, shifted by a propagation delay from the magnetometer observation point in the solar wind to the Earth.

Continuing work with the EUV instrument has led to the ability to map the He+ content integrated along the camera lines of sight into the magnetic equatorial plane. It has also led to the ability to verify the many circumstances in which the apparent outer "edge" of the He^+ envelope corresponds to the actual plasmasphere boundary, as determined from the RPI (Radio Plasma Imager) instrument on IMAGE [107], when IMAGE crosses that boundary earlier or later on the same orbit [108].

The images in Figure 7 show, in dramatic fashion, the diminution in plasmasphere size that can occur as the result of an interval of enhanced coupling of solar-wind energy to the magnetosphere. The image at the left, representing quiet conditions, shows a plasmasphere extending well beyond $4 R_E$ (dashed circle) at most local times. The image at the right shows a well-defined outer limit to the He^+ brightness across the night side. This apparent plasmapause boundary curves inward inside $3 R_E$ in the dawn sector, and appears to remain near that radius across the dayside. (The slanting brightness variation running from 10 LT into the afternoon sector is an artifact of the differences in the fields of view of the three cameras involved.)

The regular availability of plasmasphere images acquired at intervals of 10 minutes over orbital segments of several hours has led to important advances in understanding of plasmasphere dynamics during the various phases of magnetic storms [12, 109, 110]. Spasojeviæ et al. [12] have used the EUV data to obtain equatorial cross sections of the plasmasphere during magnetic-storm events as the plasmasphere radius on the nightside is sharply reduced and the apparent steepness or scale width of the plasmapause is reduced, as well. The inward displacement of the boundary was found to be most pronounced in the post-midnight sector, a result consistent with earlier findings from whistlers. However, the global scale of the view has made it possible to observe previously unknown features, such as the tendency for any preexisting irregularities in nightside plasmasphere radius to disappear as the plasmapause forms a smooth curve (on spatial scales of a few tenths of an R_E). The EUV data also show a feature only hinted at in earlier work, namely, a sunward surge of plasma on the dayside during the erosion activity on the nightside.

A distinctive feature of the right-hand record in Figure 7 is a plume extending outward from the main body of the plasmasphere, in this case at 18 MLT. Evidence of such features extending outward in the afternoon-dusk sector has previously been obtained from the in-situ perspectives of satellites [111-113], and from ground-based whistlers [114-116]. Such features were predicted in some of the earliest attempts to model the dynamic behavior of the plasmasphere during an erosion event [117]. However, this has been the first opportunity to investigate plume development in real time on a global scale.

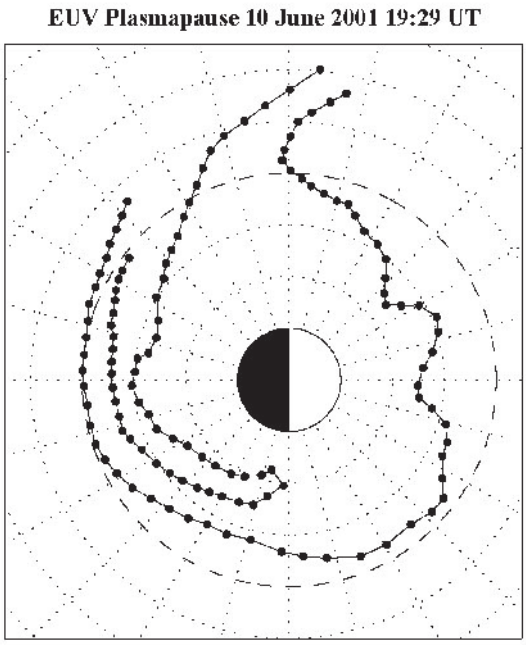

Figure 8. The magnetic equatorial configuration of the plasmasphere during a period of deep quieting following plasmasphere erosion activity on June 10, 2001 (from [12]). A low-density channel appears on the nightside between the main body of the plasmasphere and an outlying feature that earlier appeared as a density plume extending sunward from the dusk sector. Another more recently formed plume appears in the dusk sector. The plasmasphere outline was scaled from an EUV global image.

Figure 8, from [12], shows a remarkable example of the development of plasmasphere structure in the recovery phase of a storm, as a previously sunward-extending plume begins to wrap around the plasmasphere under the combined influence of the Earth's co-rotational dynamo and the reduced but ongoing convection activity that is often present at such times. As the result of the nonuniform rotation of the plume with the Earth, a cavity develops between the main plasmasphere and the plume, extending across the nightside of the Earth, while near dusk a new plume develops, apparently as a consequence of the ongoing weak substorm activity.

6.2 Outstanding Problems in EUV Imaging

Photon imaging of the plasmasphere is just beginning, and allows for pursuit of many important questions. To what extent does the plasmasphere rotate with the Earth, and to what extent can one model the flow of plasma by simply combining the equipotentials established by the solar-wind dynamo with an assumed distribution from co-rotation? How much plasma is lost to the magnetopause during a storm or substorm, and how much is lost due to storm-time interchanges with the ionosphere? How granular is the plasmasphere? On what scales can the granulation be measured? How does the plasmasphere interact with the hot plasmas of the plasma sheet during storm/recovery cycles? What can be learned from auroral data on IMAGE about the relations between precipitation into the ionosphere and plume-like extensions of the plasmasphere?

7. Radio Sounding of the Plasmasphere at High Altitudes

7.1 Sounding by the Radio Plasma Instrument on the IMAGE Satellite

Radio sounding has been highly successful in remote sensing of the Earth's ionosphere, both from the ground and from the topside ionosphere. The ISIS series of satellites, among others, created a rich body of knowledge and experience, which is currently being extended through operation of a sounder at high altitude, the Radio Plasma Imager (RPI) on the IMAGE satellite [107]. Since April, 2000, RPI has been operating in a polar orbit with apogee at $\sim 8 R_E$ and perigee ~1200 km altitude [118].

The general range-versus-frequency forms of RPI echoes returning from various locations in the plasmasphere tend to agree with pre-launch predictions [119, 120]. However, they have unexpectedly exhibited range spreading of the kind observed during topside sounding in the auroral zones [121], with indications of both coherent scattering from irregularities near the spacecraft and a variety of other interactions with density structures that appear to be field aligned [120]. In contrast, those RPI echoes that do exhibit discrete forms are of an unexpected kind, one that follows geomagnetic-field aligned paths, often into both the local and the conjugate hemispheres [118]. The discrete returning signals allow for direct study of the plasma distribution along the field lines, a subject of great interest because of the dynamic nature of that distribution [122].

Figure 9a shows a plasmagram, analogous to an ionogram but with virtual range in Earth radii plotted upward versus sounder frequency. The traces on the plasmagram are echoes propagating for the most part in the right-hand extraordinary mode (R-X), along field-line paths near $L = 3$ within the plasmasphere. Figure 9b shows a simplified diagram of the location of IMAGE in the southern hemisphere at $-24°$ and $L \sim 3$. Two field-aligned propagation paths are indicated, path A into the local hemisphere and path B into the northern, conjugate, hemisphere. In Figure 9b, the echo from path A begins at zero range at f_X, the X-mode cutoff frequency of ~240 kHz, while the echo from path B begins at an undefined long range at the same frequency. Also seen above in Figure 9a is an echo that represents the sum of delays along paths A and B (see the caption of Figure 9 for more details).

From plasmagrams of the kind illustrated, it is possible to construct the field-line density distribution from the data through established as well as newly developed inversion techniques [123]. Figure 10 shows the profiles obtained from a series of field-line echoes in coordinates of density versus magnetic latitude, obtained along a single IMAGE orbit as the satellite moved through the plasmasphere [123].

The remote-sensing experience of the plasmasphere by radio sounding, using both the direct and field-aligned echoes, indicates a region regularly permeated by small-scale irregularities [120, 124]. RPI has therefore extended to high altitudes evidence of types of sounder interactions with plasma structures already familiar from near-equatorial low-altitude work, as well as auroral zone studies.

The richness of the O- and X-mode sounding data from RPI is being augmented through study of echoes obtained both in the whistler mode and the Z mode [125, 126]. In both cases, there is substantial activity during low-altitude soundings, below about 5000 km altitude, allowing for study of density in regions that are not easily reached by the free-space mode echoes being observed from higher-altitude IMAGE locations.

7.2 Outstanding Problems in Radio Sounding of the Plasmasphere

What is the origin and distribution of the irregularities that are observed both inside and outside the plasmasphere?

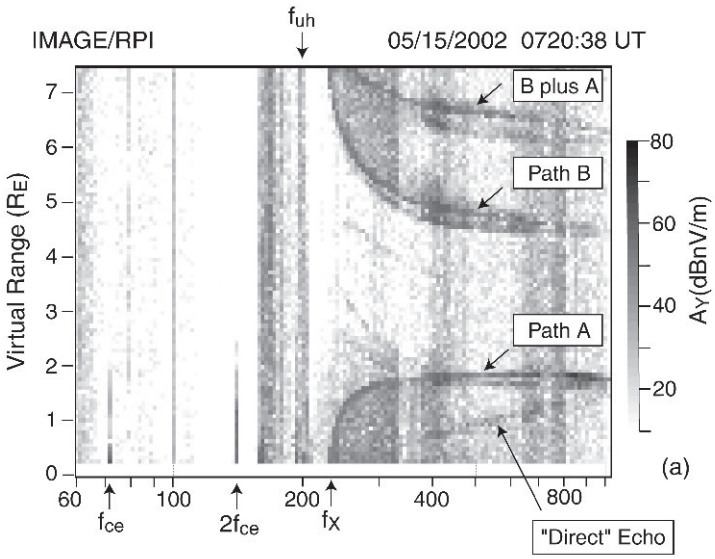

Figure 9. (a) A RPI Plasmagram from May 15, 2002, showing in coordinates of virtual range (range assuming speed of light propagation) versus sounding frequency examples of X-mode echoes that propagated along geomagnetic-field-line paths both into the local (Southern) hemisphere (Path A) and into the conjugate hemisphere (Path B).

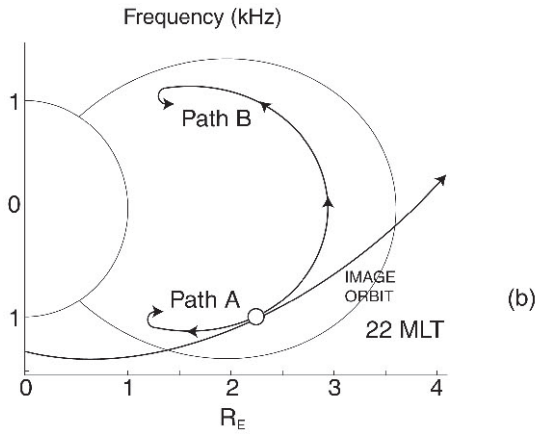

Figure 9. (b) A diagram of the IMAGE location in the plasmasphere and the directions along field lines of Path A and Path B. The ranges of the echo marked B plus A represent a combination of the ranges for Path A and Path B, implying that after initial reflection, propagation continued back and forth along the same discrete field-line path. At this time, IMAGE was moving just inside a geomagnetic-field-aligned cavity in the plasmasphere, where electron density was a factor of approximately three less than in the adjacent (outer) region. The echoes with ranges slightly shorter than those of the stronger traces in (a) are also believed to have propagated along essentially field-line paths, possibly in a whispering gallery mode at the outer edge of the density cavity. At bottom is a "direct" X-mode echo, relatively weak in comparison to the field-line echo, but with form expected for propagation deeper into the plasmasphere in a direction generally transverse to the field lines [119, 120].

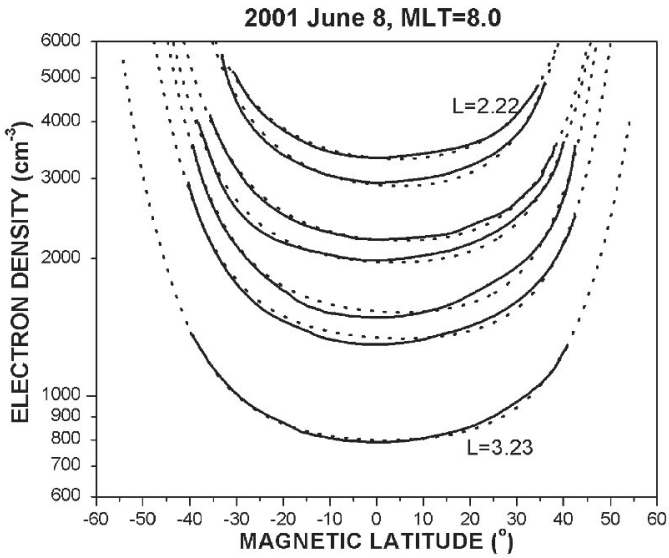

Figure 10. Profiles in coordinates of electron density versus magnetic latitude, obtained by inversion of echoes detected on a series of RPI soundings along a single IMAGE orbit through the plasmasphere on June 8, 2001 (from [123]).

What can be learned about the physics governing the field-line plasma distributions in the polar regions and within the plasmasphere (see, for example, [127])? There are many longstanding issues involving the Z and whistler modes, and about coupling between modes, that can be studied using RPI (see, for example, [128]). There is much to learn about the operation of a sounder, for example, about the behavior of a long-wire electric antenna in the plasma. That problem has always been considered a difficult one (see, for example, [130]), and it has complicated the efforts to do direction finding with the three-axis RPI antenna system. It was previously thought that the special class of sounder echoes found to be returning to RPI from the geomagnetic-field-line direction would provide a clear basis for multiple-antenna calibration and, hence, for achieving a general direction-finding capability. However, the observed field-line echoes have not provided the consistently unambiguous directional information that was anticipated. This is believed to be attributable to the tendency of the returning signal to be a superposition of waves arriving with a random distribution of wave normals within a cone around the magnetic-field direction [Bodo Reinisch, personal communication].

8. A Suggested New Term: Plasmasphere Boundary Layer (PBL)

Much attention within the space-physics community is paid to boundary layers, such as the Low-Latitude Boundary Layer (LLBL) at the magnetopause, and the Plasma-Sheet Boundary Layer (PSBL) at the edge of the plasma sheet in the Earth's magnetic tail. Such layers tend to develop at interfaces between plasmas that have distinctly different properties when considered as fluids, or on the basis of kinetic descriptions (see, for example [131, 132]). Curiously, the plasmapause region is almost never described as a boundary layer, in spite of: (1) the fact that it has been associated with locations where the cool dense plasmasphere may overlap with, or otherwise be in close proximity to, the hot plasmas of the plasma sheet and ring current [133, 134]; (2) widespread belief in a shielding effect, whereby nightside juxtapositions of hot and cold plasmas give rise to currents flowing along geomagnetic field lines and associated electric fields that dynamically "shield" the interior of the main plasmasphere from a higher-latitude flow pattern (see, for example, [133-135]). Part of the problem may be that many introductory discussions of plasmasphere dynamics, in particular those in textbooks, tend to describe the erosion and recovery of the plasmasphere in simple MHD terms: a newly developed plasmapause emerges as a topological consequence of the existence of two plasma-flow regimes perpendicular to **B**, one induced by the rotating Earth and the other by the solar wind as it impinges upon the magnetosphere (see, for example, [136, 137]). Such discussions regularly treat plasmasphere dynamics in terms of a "Last Closed Equipotential" (LCE) of the combined cross-**B** flow regimes. This is a pedagogically attractive device that tends to deflect attention from important questions about specific physical processes that may, in concert with the dynamo sources underlying the main flow, contribute to plasmasphere erosion; interchange instabilities; turbulence and the formation of irregularities; heating of the plasmapause region; energetic particle precipitation; fast, latitudinally narrow westward flows during substorms; etc. In reaction to this situation, and as a step toward more balanced and penetrating introductions to the physics of the plasmasphere, it would seem appropriate to add the concept of a Plasmasphere Boundary Layer (PBL) to our lexicon. It is noteworthy that as long ago as 1974, M. Rycroft and J. Lemaire acted as conveners of a symposium on the physics of the plasmapause at the second European Geophysical Society meeting [139], and that in 1983, J. Green and J. Horwitz organized a conference at the NASA Marshall Space Flight Center on physical processes in the plasmapause region [140].

9. Concluding Remarks

Interest in the plasmasphere has recently surged, with the development of new or more refined remote sensing tools and with an associated increase in awareness of the region's geophysical importance. Increasing attention is now being paid to the broad subject of interactions between the cool plasmasphere and hot plasmas injected during storms and substorms. Important questions are being asked about the fate of plasma eroded from the plasmasphere and convected sunward. Many areas have yet to receive the attention they deserve: for example, we still do not know exactly how a new plasmapause is formed, nor do we know much about the role of instabilities in creating or modifying the properties of that boundary region. Furthermore, we have only rudimentary knowledge of the coupling of the plasmasphere to the nonuniform underlying ionosphere. In short, there is much to do, and remote sensing will surely play an important role in this future work.

10. Acknowledgment

This review is dedicated to the memory of Yela Bogitch, who always symbolized for me the best that is URSI. I wish to acknowledge important contributions to the preparation of the review by A. J. Smith, M. A. Clilverd, P. Chi, J. C. Foster, X. Huang, M. Spasojeviæ, J. Lemaire, and B. Reinisch. Their comments and those of other colleagues are deeply appreciated. Part of the preparation of this review was supported by subcontract No. 03-08482 to Stanford University from the University of Massachusetts Lowell.

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