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# The plasmasphere and advances in plasmaspheric research

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**Abstract**

A review is made of recent major advances in plasmaspheric research; important results have emerged from those concerning a variety of plasmasphere features. Both experiments and modeling efforts have progressed. A number of unknowns still persist, however, but research is underway toward their clarification. These clarifications are essential for obtaining a predictive capability of the near-Earth space weather in the plasmasphere region. 

*Keywords:* Plasmasphere; Inner magnetosphere

## 1. Introduction

The plasmasphere, unknown in 1950, is an important and sizable part of the near-Earth space environment. It is not only of considerable inherent scientific interest, but a number of communications, navigation and military satellites that have become indispensable to routine human activities are stationed in this region. To ensure their accuracy and reliability, it is important to understand fully the medium in which they operate. For these reasons, there has been an ongoing attempt to understand the plasmaspheric environment, its sensitivity to external forcings, and its dependence on observable parameters.

Unlike the polar region, where the magnetic field lines are open and merge with the interplanetary magnetic fields, the plasmasphere environment is characterized by magnetic field lines that are closed and approximately dipolar. This background geomagnetic field configuration leads to unique plasma dynamics that provide the plasmasphere with its distinctive characteristics. While the polar region has been extensively studied (Schunk, 1989; Ganguli, 1996), the plasmasphere has attracted comparatively less attention over the last four decades. Consequently, accurate models of the plasmasphere are still under development and are being refined.

The need for a reliable model for the high-altitude plasmasphere has become especially important now because of three imaging missions, NASA/IMAGE (Burch, 1996), DoD/ARGOS (McCoy et al., 1995), and the proposed Magnetospheric Imager (MI), whose objectives include imaging the plasmasphere. As explained by Roelof et al. (1992), an important but substantially unresolved issue confronting remote sensing experiments is the extraction of qualitative and quantitative physical information from the observational data. Satellite imagers will record the UV sunlight scattered from $He^+$, $O^+$ and other ions in the plasmasphere. These sensors view the plasma along a single line of sight, receiving the sum of all the light scattered into this path but giving little information about the distance to the scatterer. In order to use this information fully, researchers need an accurate model of the plasmaspheric structure.

The geomagnetic conditions in the high-altitude plasmasphere, which consist of a joint action of the Earth's corotation field and magnetospheric convection on the closed dipolar field lines, add to the complexities of this region. The difference between open and closed geomagnetic field configurations is quite significant in that a variety of plasma populations with significantly different characteristics can be supported in the plasmasphere, which can complicate the

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analysis of this region (Lemaire and Scherer, 1974; Lemaire, 1989). The action of the corotation and magnetospheric convection on these different populations leads to unique configuration and density asymmetries in the outer flux tubes at different local times. The interplay between these populations and the full scope of physical effects vis-à-vis plasmaspheric morphology and dynamics have yet to be fully appreciated. Such knowledge is not only scientifically compelling, but, as noted earlier, is crucial for ensuring the accuracy and reliability of space-based instruments as well as for the analysis and interpretation of observations of the inner magnetosphere.

A thorough review of the history and development of plasmaspheric research is contained in the exhaustive monograph by Lemaire and Gringauz (1998). In addition, a snapshot of the current state of research can be found in a Special Issue of this journal (Lemaire and Storey, 2000) which contains papers from a special session of the 27th URSI General Assembly honoring Donald Carpenter that was held on 14 August 1999 in Toronto, Canada. Because of the flurry of activity in this field in recent years, this paper can only highlight some of the recent advances in plasmaspheric research. We do not intend to be exhaustive, but only to give a flavor of some the outstanding issues and the methods that have been employed to address them. In this vein, Section 2 highlights some of these outstanding issues. Section 3 looks at the recent observations and Section 4 the recent theoretical attempts to understand those observations. Finally, Section 5 sums up the state of the field at the current time.

## 2. Major outstanding issues

A series of recent articles (Carpenter, 1995, 1997; Carpenter and Lemaire, 1997; Moldwin et al., 1997; Carpenter et al., 2000) highlights the significant gaps in our understanding of the physical processes in the plasmasphere despite three decades of study. It could be concluded from these studies that the three main areas in need of more detailed understanding are the following: (1) plasmaspheric dynamics during geomagnetic storms, (2) the refilling of the plasmasphere after a geomagnetic storm, and (3) the coupling between the plasmasphere and the ionosphere. We have yet to explain satisfactorily how the plasmasphere is eroded during a geomagnetic storm, and the reformation of the plasmapause boundary and the refilling of flux tubes after a geomagnetic storm. In addition, significant structuring in the plasma density is observed at higher altitudes, the origin of which has yet to be unambiguously established. We neither have a clear picture of the observed density and temperature enhancements at higher altitudes, nor do we fully understand the origin and the role of waves often observed in the plasmasphere. Another major issue is the morphology of the plasmapause and the physical processes that determine its shape. In response to these needs the community has directed the research activities in both experiments and modeling. In the following we review the latest developments.

## 3. Measurements in the plasmasphere

Both in situ and whistler measurements led to the discovery of the plasmasphere in the 1960s (Lemaire and Gringauz, 1998). While these techniques are still being vigorously applied (see, for example, Menk et al., 1999), new measurement techniques are being developed in order to obtain finer details and to probe the physics that is not accessible to the established measurement techniques. For example, Calvert et al. (1995) discussed a method of satellite-based radio sounding of the plasmapause, and Meier et al. (1998) presented an image inversion technique for remote sensing in the EUV range. These techniques will be used for measuring global plasmasphere properties by the IMAGE satellite. Yoshikawa et al. (1997) and Nakamura et al. (2000) have confirmed that helium EUV emissions can be used to image the plasmasphere. Some features, such as the morphology of whistler ducts, which are not easily probed by the above techniques, have been investigated by satellite-beacon radio-interferometer arrays (Jacobson et al., 1996; Hoogeveen and Jacobson, 1997a,b). The results from these and other observational studies are described below.

### 3.1. Density distributions and structures

Measurements of density in the plasmasphere have been a major focus during the last five years. Consequently, a large number of publications have resulted in this area. Perhaps the most intriguing features, which have defied satisfactory explanation, are the observations of fine structure in the plasma density in the outer plasmasphere (Moldwin et al., 1995, 1996, 1997) and the existence of density cavities filled with waves (Carpenter et al., 2000).

Using data from the magnetospheric plasma analyzer (MPA) on board the Los Alamos geosynchronous satellites, Moldwin et al. (1995) observed fine-scale density structure in the dusk sector of the outer plasmasphere. They also determined that the presence of fine-scale structure is correlated with substorms and is possibly caused by the penetrating electric fields associated with a substorm. Fig. 1 shows the normalized standard deviation of the density for the 1-h intervals that were associated with substorms and those that were not. The level of variability in the substorm-associated intervals was significantly higher than in those not associated with substorms. Thus, it was concluded that the level of variability of density in the outer plasmasphere generally increases with increasing geomagnetic activity. The high variability intervals are not found to be associated with large negative values of *Dst*, but are associated with substorm activity as indicated by *Kp* and by energetic electron injections.

Analyzing CRRES sweep frequency receiver data, Carpenter et al. (2000) conducted a thorough investigation into the properties of density cavities which are frequently observed (Carpenter, 1970; Taylor et al., 1971; Chappel, 1974). They report deep density troughs inside the

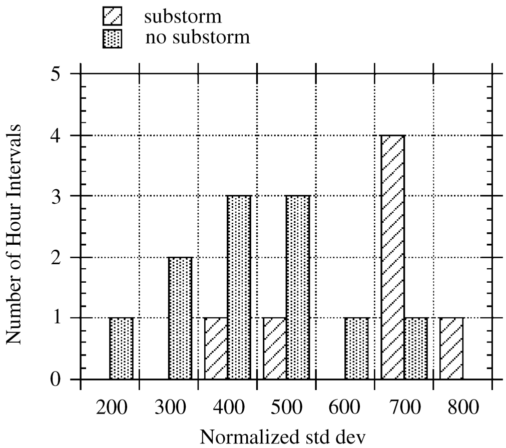


Fig. 1. Histogram of the value of the normalized standard deviation of the density for the 1-h intervals that were associated with substorms and those that were not. The substorm-associated intervals have higher variability than those not associated with substorms. (Fig. 7 from Moldwin et al., 1995.)

plasmasphere, in which the electron density is far below nearby plasmasphere levels. These troughs are especially pronounced in the aftermath of plasma erosion episodes and are most commonly found between dusk and midnight. A typical example of such a trough near $L\sim3$ and around 22 magnetic local time (MLT) is given in Fig. 2. These deep density troughs are typically accompanied by waves that are trapped inside the trough, and are found to be of higher frequency than the background waves. Besides the density troughs, the low-energy plasma analyzer on CRRES also revealed significant fluxes of 10 eV–30 keV electrons trapped on plasmaspheric field lines (Burke et al., 1995). These electrons exhibited banded structures in an energy versus time spectrogram. It was determined that these banded structures are a natural occurrence of plasma sheet cloud capture in the inner magnetosphere (from a sudden decrease in magnetospheric convection), resulting from the energy-dependent drift of the electrons around the Earth (Liemohn et al., 1998).

Other interesting global consequences of plasmaspheric dynamics have also been recently discovered. For instance, Elphic et al. (1996) (see also Su et al., 2000a,b) have seen coexistent plasmaspheric and magnetopause plasma in the LANL MPA data set. This has led Elphic et al. (1997) and Borovsky et al. (1997) to conclude that the plasmasphere could be a major contributor of dense and cold plasma found in the plasmasheet. Investigations of other global features, such as the plasmapause motion, were also discussed. Recently, LANL data have been used to quantify the timescales of the cold plasma refilling process (Lawrence et al., 1999; Su et al., 2000b). In addition, Afonin et al. (1997) used Cosmos 900 observations to shed new light on the formation of the plasmapause in the post-midnight sector and on the time-dependent electric field distribution in the night-

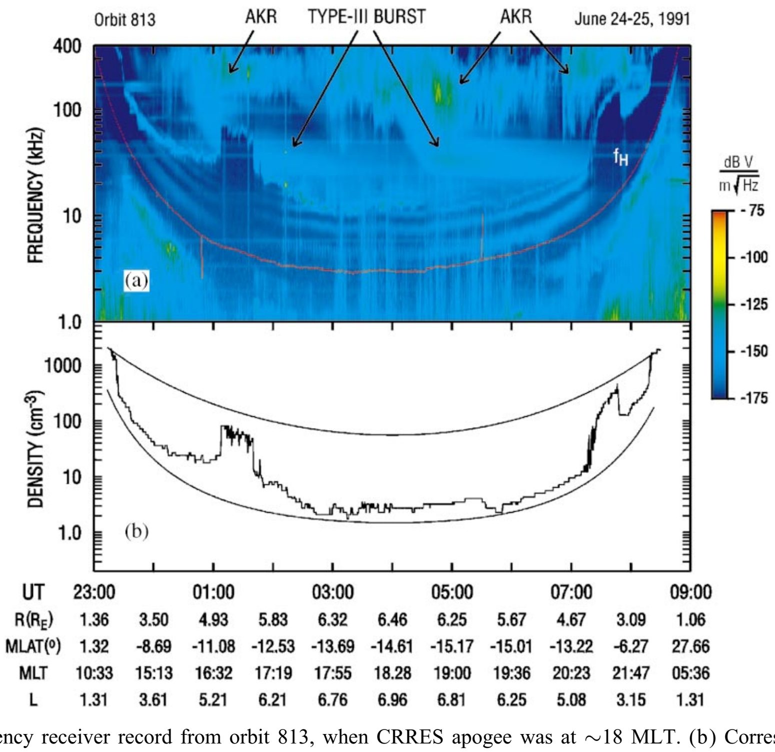


Fig. 2. (a) Sweep frequency receiver record from orbit 813, when CRRES apogee was at ∼18 MLT. (b) Corresponding electron density plot, showing evidence of a well-defined plasmaspheric cavity at the right. (Fig. 6 from Carpenter et al., 2000.)

side sector before and during a geomagnetic storm. Kasaba et al. (1998) described how the plasmapause can be remotely sensed with observations of nonthermal continuum behavior.

In situ measurements from a number of other satellites, such as Akebono, INTERCOSMOS-24, MAGION-2, and Hinotori, have further refined our knowledge of the global electron density distributions within the plasmasphere (Kimura et al., 1995, 1997; Fatkullin et al., 1995; Su et al., 1995). Electron density variations along a geomagnetic field line for different $L$ values have been studied by whistler data analysis (Singh and Singh, 1997). They found that the equatorial electron density slightly increases with $L$. The dynamics of the plasmasphere during magnetic storms (Jiricek et al., 1996) and quiet times (Lalmani et al., 1996) have also been characterized.

### 3.2. Temperature distributions

Although there has traditionally been much activity in density measurements (Section 3.1), there has been relatively weaker interest in the measurement and modeling of the temperature morphology of the plasmasphere. However, the temperature and heat flow in the plasmasphere are critical components of a complete picture, and several important studies have been made.

Using DE 1 satellite data, Comfort (1996) provided a good review of the plasmaspheric thermal structure; he concluded that it is closely tied to the density structure and has a significant bearing on the composition of the plasma. For instance, strong temperature gradients are found to be co-located with strong density gradients. In addition, the role of the photoelectrons in energizing the ions in the plasmasphere was examined and it was found that they cannot always explain the observed high ion temperatures. Finally, Comfort (1996) pointed out that an outstanding issue of substantial importance is the mechanism by which heat is transferred from hot to cold ions. Coulomb collisions are not always sufficient to achieve this, and other mechanisms, e.g., wave–particle interactions (e.g. Khazanov et al., 1996a, 1997), could be critical.

A number of large-scale analyses of temperature structure have been conducted. Oyama and Abe (1995), Oyama et al. (1996), and Abe et al. (1997) have used Akebono data systematically to measure electron temperature in the plasmasphere, yielding new insights about its formation. Also, Titheridge (1998) has developed a model for the electron and ion temperatures. These studies, in addition to the scientific advancement of each study, are developing a baseline for our understanding of temperature and heat flow in the plasmasphere.

### 3.3. Magnetic pulsations and waves

Waves play an important role in the overall dynamics of space plasmas. They not only act as a useful diagnostic of the relevant physical processes, but they can also affect the macroscopic plasma state by influencing the transport properties. As mentioned in Section 3.2, small-scale waves can be an important means to dissipate energy in collisionless plasmas, thereby influencing the thermal state of the plasmasphere. Similarly, large-scale waves can reflect the global morphology of the plasmasphere. Hence, there is a substantial interest in the measurement and characterization of waves in the plasmasphere. Several key measurements and their implications are listed below.

Fraser et al. (1996) used the observations from the triaxial fluxgate magnetometer on the CRRES satellite to study the electromagnetic ion cyclotron waves near the plasmapause. Their Poynting vector calculations indicated that in most cases energy propagates away from the equatorial region and the energy flow is mainly along the magnetic field. This was interpreted as evidence for the possible existence of an equatorial source for these waves, but the nature of the generation mechanism is not entirely clear. Ondoh (1996) analyzed ISIS-1 and ISIS-2 data to report that narrow-band hiss around 5 kHz is often observed in the vicinity of the plasmapause, and that it correlates well with ground-based observations of narrow-band hiss at mid- and low-latitudes. Using these results, he concluded that the energetic electrons convected from the tail in the vicinity of the equatorial plasmapause are generating the hiss.

Oya (1997) observed so-called "donkey ear" plasmaspheric density structures in the Akebono plasma wave measurements, which are perhaps similar to those observed by Olsen (1992) in the DE 1 data. He also proposed a mechanism to explain this phenomenon involving the modulation of plasma densities by the induction electric field (due to $\mathrm{d}B/\mathrm{d}t$) created by the ring current. Osaki et al. (1998) used Akebono observations of magnetic field, electric field, and electron density to study the properties of Pi2 pulsations in the plasmasphere. Using AMPTE/CCE data, Fuselier and Anderson (1996) investigated wave interactions between sunward-convecting plasmaspheric ions with hot-plasma-generated ion cyclotron waves during geomagnetic disturbances. By analyzing the particle distribution functions, they showed that plasmaspheric $He^+$ but not $H^+$ resonates with these waves and is transversely heated during its outward convection.

## 4. Modeling of the plasmasphere

During the last five years there has also been a strong effort in the theoretical direction. Advances have been made in both global and microscopic (e.g., wave–particle interactions) modeling of the plasmasphere. The global modeling effort has progressed along two different paths, with both *ab initio* (first-principles-based) and empirical approaches. As noted earlier, the need for an accurate global model is particularly important now since it will be necessary to appre-

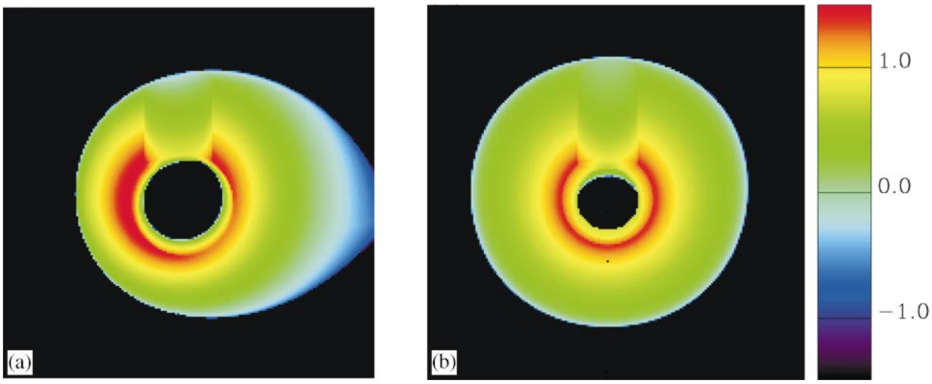


Fig. 3. Synthetic 30.4 nm images of the plasmasphere generated by MSKPM, as viewed from $7R_E$ above the geographic North pole. The plasmapause as determined by the last closed equipotential (a), and by the interchange instability mechanism (b).

ciate fully the EUV imaging data of the plasmasphere that will soon become available.

### 4.1. Ab initio modeling

Considerable effort on different aspects of first-principles-based modeling techniques has been made, and these models have greatly enhanced our ability to study the plasmasphere quantitatively. For simplicity, we broadly categorize these models into the following subcategories: global dynamics and structure; ionosphere-plasmasphere coupling; and energetic particle–plasmasphere coupling.

#### 4.1.1. Global dynamics and structure of the plasmasphere

The formation of density troughs in the outer plasmasphere was addressed by Ober et al. (1997) using a fluid description that follows convecting flux tubes. This dynamic global core plasma model (DGCPM) uses Tsyganenko (1989) magnetic fields and convection electric fields from the ionospheric convection model of Sojka et al. (1986) to move the flux tubes as they are populated with cold plasma using the refilling rates of Carpenter and Anderson (1992). The model is used to investigate the effects of sub auroral ion drifts (SAID) on the formation of density troughs during periods of high magnetic activity. DGCPM results indicate that steep gradients in the electric potential present during the SAID event can be responsible for developing fine structure in the plasma density distribution.

Kinetic effects can introduce physics, such as contraction and rarefaction in velocity space and unique trapped particle dynamics, which are not accessible to a fluid model. Reynolds et al. (1997, 1999) developed a multi-species kinetic plasmasphere model (MSKPM) to investigate the convection of magnetically trapped thermal particles. The model incorporates the convection electric field of McIlwain (1986), a dipole magnetic field, and focuses on the ion exosphere, which is collisionless and where the convection of trapped particles can be important. Also, MSKPM defines the plasmapause according to the interchange instability criteria put forth by Lemaire (1974). When flux tubes are far from Earth (at dusk), the trapped population has a lower density than when the flux tubes are close to Earth (post midnight). The model predicts that these radial excursions result in increased density, increased parallel temperature, and decreased perpendicular temperature in the post-midnight sector where the flux tubes are closest to Earth.

MSKPM was used to generate synthetic images of the 30.4 nm line from $He^+$ for an anticipated IMAGE orbit (Ganguli et al., 1998). It was found that the choice of plasmapause definition provides a distinguishable signature in the synthetic images. The physical mechanisms active at the plasmapause can be deduced through a comparison of model output with observations. Fig. 3 shows synthetic images from a polar perspective for two different choices of convection field and plasmapause definition. Fig. 3(a) uses a uniform electric field and the last closed equipotential definition of the plasmapause (Brice, 1967). Fig. 3(b) uses the electric field model of McIlwain (1986) and the interchange definition of the plasmapause. The shape of the plasmapause clearly is the dominant effect. The images are significantly different in both magnitude and topology to make a clear distinction regarding the plasmapause position. Further improvements to MSKPM in the form of a more realistic local-time-dependent exobase (Reynolds et al., 2000) are currently being implemented.

Lemaire (1999) has developed a hydrostatic equilibrium model and investigated the convective stability of the plasmasphere. The analysis shows that a hydrostatic model is not able to reproduce the equatorial electron density distributions observed by the ISEE satellite (and parameterized by Carpenter and Anderson, 1992) following prolonged periods of quiet magnetic conditions for $L < 8$. The reasoning for this conclusion is threefold: (1) the saturated plasma density profiles are characterized by scale heights which are independent of $L$, and do not agree with the profiles predicted by hydrostatic models; (2) calculated barometric equatorial density profiles have a minimum value at an equatorial distance given by $L_0 = 6.6(\Omega_E/\Omega)^{\{2/3\}}$ where $\Omega_E$ and $\Omega$ are the Earth and plasmasphere angular rotational speeds, respectively, while no such minimum is apparent in the ISEE data; and (3) it is shown that for $L > L_0$ all barometric models are convectively unstable to interchange and quasi-interchange instabilities. Lemaire (1999) concludes from this study that the plasmasphere is not in hydrostatic equilibrium but in a state of continuous hydrodynamic expansion. Pierrard and Lemaire (2000) show that a spatially dependent fractional density of trapped particles can, however, agree with the quiet equatorial density profile of Carpenter and Anderson (1992).

More recently, Lemaire (2000) has suggested a new two-step mechanism for the formation of plasmaspheric tails. The mechanism is initiated by an enhancement of the dawn-dusk component of the electric field in the dayside magnetosphere associated with a substorm event. The day–night asymmetry of the plasmasphere develops first and creates a bulge in the pre-noon local time sector. Next, the bulge drifts into the afternoon sector under the influence of eastward convection. Since the convection velocity is a decreasing function of $L$, the tip of the bulge has a smaller azimuthal drift velocity than its base, which is closer to the Earth. Therefore, the tip of the bulge trails behind its base. This leads to the formation of the plasma tail gradually in the dayside while the stretching bulge is convected into the afternoon-dusk sector.

#### *4.1.2. Ionosphere–plasmasphere coupling*

A number of notable efforts have been made in modeling the coupling between the plasmasphere and the ionosphere. Bailey et al. (1997) (more details are given in Bailey and Balan, 1996) describe a multi-species fluid model in which time-dependent equations of continuity, momentum, and energy balance are solved along eccentric dipole magnetic field lines for densities, field-aligned fluxes, and temperatures of different ion species and electrons. The model was applied to study the effects of the vertical **ExB** drift, neutral wind, and the plasma fountain on the distribution of electrons in the equatorial topside ionosphere. It was reported that the fountain can rise to altitudes of around 800 km at the equator and can cover the magnetic latitudes of about $\pm 30^{\circ}$. The model electron temperatures were compared with observations made by the Hinotori satellite at 600 km. Moffett et al. (1996) describe a coupled model of the thermosphere, ionosphere, and the plasmasphere. The model has been applied to study the behavior of field-aligned ion fluxes in the topside ionosphere in the mid- to low-latitude regions. It is found that interhemispheric asymmetries can arise readily from the different offsets of the geomagnetic and geographic poles without any asymmetry in the inputs.

Guiter et al. (1995b,c) used a similar time-dependent one-dimensional hydrodynamic model for plasmaspheric flows to study the distribution of $O^+$ ions. The model is interhemispheric and simultaneously solves the equations of continuity, momentum, and energy equations for a two-ion ($H^+$ and $O^+$), quasi-neutral, currentless plasma. They concluded that $O^+$ is responsible for the annual density variation in the plasmasphere (Guiter et al., 1995c), and that it critically determines other plasmaspheric parameters (Guiter et al., 1995b).

Other advances have also been made in ionosphere–plasmasphere coupling. For instance, Cole (1995) determined a plasmaspheric impedance on the ionospheric current system from longitudinal pressure gradients. Comfort et al. (1995) re-examined thermal conductivities along plasmaspheric field lines. The effects of anisotropic thermal conductivity on the temperature structure of the ionosphere–plasmasphere have been described by Khazanov et al. (1996b). Finally, Pierrard and Lemaire (1996) found that temperature inversions in the plasmasphere can be explained with a Lorentzian velocity space distribution in the topside ionosphere.

#### *4.1.3. Energetic particle–plasmasphere coupling*

In the inner magnetosphere there are a number of hot plasma components of the distribution function. Among these are photoelectrons, ring current and plasma sheet particles, and the relativistic radiation belts. A number of studies have focused on the interaction of these populations with the plasmasphere.

Photoelectrons are created in the ionosphere when extreme ultraviolet light ionizes upper atmospheric neutral particles. Because of their high mobility, they can escape from the ionosphere and quickly traverse the field line through the plasmasphere, and a few of them get scattered into the geomagnetic trap. Once here they are long lived and slowly deposit their energy to the thermal plasma in this region. These various stages of photoelectron evolution can all influence the cold plasma population, and all have been studied in recent years. For instance, Guiter et al. (1995a) examined the influence of photoelectron heating on plasmaspheric temperatures. Also, Liemohn et al. (1997) combined the Guiter thermal plasma model and the Khazanov and Liemohn (1995) photoelectron model to calculate self-consistently the collisional and electrodynamical coupling between these populations. They determined that during the first stage of refilling, before the ionospheric streams interpenetrate, this hot population can significantly influence the cold plasma flow (see also Liemohn and Khazanov, 1998). The long-term heating of the thermal electrons was investigated by Khazanov et al. (1998), who concluded that, in the dayside plasmasphere, photoelectrons are the strongest and most persistent source of energy.

The ring current region is a high-energy belt, which can influence the plasmasphere structure and dynamics through the injection of a high-energy plasma component into the plasmasphere. The ring current and plasmasphere can interact with each other via multiple processes, such as Coulomb collisions, charge exchange, and wave–particle interactions. Coupling of the ring current with the plasmasphere due to Coulomb collisions was addressed by Fok et al. (1995). They found that, as the ring current ion energy degrades, a low-energy ( $< 1$ keV) ion population is formed in a background of thermal plasma. The energy transferred from the ring current ions to the plasmasphere results in enhanced plasma temperatures at high altitudes. Guiter et al. (1995c) also examined this coupling, determining that the ring current interaction was necessary to explain observed $O^+$ densities. Trakhtengerts et al. (1996) considered the formation of asymmetric ring current loops at different phases of magnetic storms based on the mechanism of ring current dissipation along with gyroresonance interaction of the ring current particles with Alfven waves. They showed that an asymmetric component of the ring current arises due to fast dissipation of the energetic ion belt at plasmaspheric bulges and detached regions, formed in the equatorial plane on the drift path of energetic ions. Bishop (1996) presented an exhaustive study of multiple charge exchange and ionization collisions within the ring current–geocorona–plasmasphere system. His study indicates that a second ring current region is formed at a lower $L$ shell. This method is useful in evaluating trapped ion fluxes on inner $L$ shells generated by the ionization of energetic neutral atoms. Also, Liemohn et al. (1999) examined the electrodynamical coupling of the ring current with the cold plasma during the early stages of refilling, determining that its effect is quite minor.

### 4.2. Empirical modeling

The plasmasphere environment is highly complex and offers considerable challenge towards developing meaningful ab initio models. Recently, Wolf and Spiro (1997) have reviewed these complexities. Often, due to the simultaneous action of different physical processes acting over highly disparate spatial and temporal scales, it is not possible to account for all the realities accurately, and approximations have to be made at the cost of completeness. This can wash out important physics, which may not be acceptable. However, physical insight into the general characteristics of plasmaspheric parameters can be gleaned from empirical models, and they serve as excellent guides and benchmarks for ab initio models. For this reason, considerable effort has been applied towards developing empirical models of plasmaspheric dynamics.

Lambour et al. (1997) have modified the data-driven Air Force Magnetospheric Specification and Forecast Model (MSFM) by including the cold plasmaspheric ion population model of Carpenter and Anderson (1992). They used this modified MSFM to examine the effect of ionospheric refilling on the cold plasmaspheric ions. They report the development and westward transport of duskside plasmaspheric plumes and tails during periods of enhanced convection and the eastward transport of these structures during decreasing activity. Galperin et al. (1997) developed a time-dependent convection-driven plasmaspheric density model to describe plasmaspheric thermal density profiles. The model is based on the convection drift and refilling rate prehistory calculated for a particular flux tube, and its most important ingredient is a realistic convection model for disturbed times. Comparison of the model output with Millstone Hill radar observations is encouraging and indicates that the model can be used to predict the locations of plasma density radial gradients, including the plasmapause. Craven et al. (1997) used DE 1 data to compile a survey of $He^+$ observations in the plasmasphere. This model will serve as a critical tool for use with the new plasmaspheric remote sensing techniques that are based on knowledge of the $He^+/H^+$ ratio. In addition, Gallagher et al. (1995, 2000) have developed a global core plasma model. It is continuous in value and gradient and is composed of separate models for the ionosphere, the plasmasphere, the plasmapause, the trough, and the polar cap.

### 4.3. Wave–particle interactions

As pointed out earlier (Section 3.3) waves are an important constituent of the plasmasphere and are frequently observed. Consequently, the theoretical analysis of their origin and role as far as global plasmaspheric dynamics is concerned is an important topic. A number of theoretical papers have focused on different aspects of waves in the plasmasphere. Khazanov et al. (1996a) studied the effects of wave–particle interactions on the ion temperature anisotropy in the equatorial plasmasphere. They found that the interaction of the hot protons of the ring current with the cold dense plasmasphere leads to the generation of MHD waves. Dissipation of these waves in the outer plasmasphere results in heating, with a maximum heating rate near the geomagnetic equatorial plane. Their calculations show that the ion temperature exceeds the electron temperature by a factor of 1.5–2.0 and that the ion temperature anisotropy can reach significant values in the evening sector.

Thorne and Horne (1996) discussed a source for electron heating in the equatorial plasmapause due to wave–particle interactions. Following the work of Hayakawa et al. (1986a,b) and Kozyra et al. (1987) for plasmaspheric hiss, they showed that lightning-generated whistlers, which enter the magnetosphere over a broad range of latitudes just inside the plasmapause, can be strongly focused by the steep plasma density gradient into a narrow range of $L$ shells near the equatorial region. Under the prevailing plasmaspheric conditions they argue that these waves are in cyclotron resonance with energetic electrons, which can lead to their dissipation through electron cyclotron damping.

Other wave–particle interactions have also been explored. Pokhotelov et al. (1997) have considered oxygen-cyclotron waves in the deep plasmasphere during magnetic storms. They suggest that the waves are generated in a multi-ion plasma by an instability involving hot oxygen ions with loss-cone or ring-like distributions. They compare their results with the ULF wave observations from the Akebono satellite and find the results promising. More recently, Pasmanik et al. (1998) have discussed a model for cyclotron wave–particle interactions at the plasmapause. Within the quasi-linear framework they construct a model for cyclotron wave–particle interactions, including real sources and sinks of particles and waves, and different regimes of pitch-angle diffusion. Also, Khazanov et al. (1997, 2000) have shown that electromagnetic waves below the ion cyclotron frequency can generate lower-hybrid waves in the outer plasmasphere, and these higher-frequency waves readily heat the cold plasma and could be the source of the equatorial plane pancake distributions, such as those seen by Olsen et al. (1987).

There has also been substantial development on the topic of plasmaspheric refilling in the context of wave–particle interactions. For one, Guglielmi et al. (1995) showed that the presence of Alfven waves in the inner magnetosphere can greatly enhance the outflow of ionospheric ions because of ponderomotive force effects. This influence was further studied by Feygin et al. (1997), who calculated refilling rates based on this interaction for various wave intensities. Also, Singh and Leung (1995, 1999) and Singh (1996, 1998) have performed the first calculations of self-consistent wave–particle interactions in the refilling process, showing that electrostatic ion cyclotron waves can be excited and induce particle trapping in the plasmasphere.

## 5. Conclusion

We have presented here a review of the principal advances concerning the Earth's plasmasphere since the last comprehensive review by Lemaire and Gringauz (1998). It is a pleasure to report that within this short-time significant inroads have been made. Furthermore, the future of plasmasphere research appears particularly exciting at this time. It is expected that with the launch of the IMAGE satellite new global imaging techniques will reveal even the deepest intrigues of plasmaspheric dynamics that have so far eluded us. One such aspect of great significance to space weather prediction is the plasmaspheric response to external forcings. Coordinations of imaging data with in situ data from deep space satellites may just make this possible. In anticipation of this possibility, modelers must attempt to couple plasmaspheric models with the existing global magnetospheric models. Efforts towards this end are underway in a number of institutions around the world.

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