Modeling the entry of magnetosheath electrons into the dayside ionosphere

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Abstract. It has recently been shown that it is possible to quantitatively model the entry of magnetosheath ions and their access to the dayside ionosphere with surprisingly good results. In the same model, electrons had access to the region poleward of the cusp at unrealistically high intensities. We improve the previous model by imposing the constraints of charge quasi-neutrality and introducing more realistic electron magnetosheath populations. It turns out that no potential drop within the cusp proper is either needed or observed in order to enforce charge neutrality, since ions, as well as electrons, can enter freely, and they originally have the same density in the magnetosheath. Poleward of the magnetic cusp, ion entry is sharply curtailed because of the tailward magnetosheath flow, and the potential required and observed rises rapidly. This potential eliminates access of the “core” population of the magnetosheath electrons to the ionosphere. The typical polar rain signature observed at low altitudes fits best with the suprathermal solar wind electron population (either halo or both halo and strahl components). The model clearly shows that ions previously identified at low altitude as “mantle” do indeed cross the magnetopause tailward of the magnetic cusp, that is, the ionospheric mantle signature consists of ions originating in the high-altitude mantle. A single ion spectrum within the low-altitude cusp proves to consist of magnetosheath ions which have crossed the frontside magnetopause from a range of positions which commences with the merging site and extends to the magnetic cusp, but which is typically only 1-3 $R_E$ wide along the direction of the field line convection.

1. Introduction

Onsager et al. [1993] demonstrated that the entry of magnetosheath ions into the magnetosphere can be accurately modeled in a straightforward manner. For a given interplanetary magnetic field (IMF) orientation, solar wind temperature and density, ionospheric convection speed, and dipole tilt angle, the Onsager model traces detected ionospheric particles back to the magnetosheath in three steps. In the first step, a model magnetic field and a model convection field are selected and used to trace the particle to the magnetopause entry point (for now the Stern [1985] model, and a simple uniform dawn-dusk electric field, respectively), along with the assumption of uniform IMF penetration in the magnetosphere [cf. Wing et al., 1995]. The second step is to compute the de Hoffman-Teller reference frame velocity [e.g., Hill and Reiff, 1977; Cowley and Owen, 1989], and hence the particle acceleration or deceleration experienced in crossing the magnetopause current layer. From this calculation, the model obtains the velocity that the particle originally had in the magnetosheath. Finally, it computes the phase space density of that type of particle with that velocity using the results of gasdynamics calculations of Spreiter and Stahara [1985]. Assuming conservation of phase space density, the model can be used to compute the differential energy flux at the location where the particle was “detected” in the ionosphere. Although Onsager et al. [1993] presented example calculations for noon-midnight meridian only, the tracing of particles from the ionosphere to the magnetopause is fully three-dimensional (although the assumed electric field was purely dawn-dusk). In fact, in the present paper, most of the calculations were done for particles that were slightly prenoon, as is typical of most Defense Meteorological Satellite Program (DMSP) dayside passes.

The Onsager et al. [1993] model in its original form does not accurately simulate magnetosheath electron entry, giving a much more extended entry region in latitude and higher cusp temperatures than are actually observed. It has previously been suggested that electron entry is limited by the constraints of charge quasi-neutrality, which can be enforced by an electric field at the magnetopause. This electric field reduces electron entry to the extent required to balance the ions, which have slower thermal speeds and hence can only enter the magnetosphere from a more limited region [Reiff et al., 1977; Burch, 1985]. In this paper, we extended the Onsager et al. [1993] model to include a mechanism to enforce the charge quasi-neutrality constraint and introduced more realistic electron magnetosheath populations. As a result, it proved possible to realistically model electron entry not only in the cusp but also in the mantle, the polar rain, and even in the...
open field line "LLBL", which lies equatorward of the cusp [Lyons et al., 1994; Lockwood et al., 1993]. The solar wind consists of three components, namely (in order of decreasing density), core, halo, and strahl [Fairfield and Scudder, 1985, and references therein]. We also extended the Onsager et al. [1993] model to include all three components as possible sources of precipitating particles. The model, unlike the real world that it tries to emulate, can turn on and off each of the solar wind components, allowing for a detailed study of the plasma sources for the precipitation regions. There have been several observational studies on the solar wind sources for polar rain [Hardy et al., 1986; Baker et al., 1987; Fairfield and Scudder, 1985]. In the present paper, by using a more sophisticated model of magnetosheath electron entry, we hope to give a unified picture of the access of magnetosheath electrons to the dayside ionosphere. Several researchers have speculated about the ranges of the particles’ entry points at the magnetopause [e.g., Smith, 1994]. The results of our research indicate that a single unified and continuous entry mechanism accounts for cusp, mantle, and polar rain electrons and that portion of the LLBL which is open.

2. Charge Quasi-Neutrality Constraint

Plate 1 shows the result of the original Onsager et al. [1993] model as displayed in the usual Applied Physics Laboratory (APL)/DMSP particle format, taking into account DMSP device sensitivity. The model spectrogram only shows spectra that are on open field lines. For comparison, a typical DMSP pass through the cusp, mantle, polar rain regions is shown in Plate 2. The input parameters to the spectrogram in Plate 1 are IMF \( B_x = 0 \) nT, \( B_y = -3.5 \) nT, and \( B_z = -3.5 \) nT, solar wind ion temperature \( = 1 \times 10^5 \) K, electron temperature \( = 1 \times 10^5 \) K, density \( = 10 \) cm\(^{-3}\), the ionospheric convection speed \( = 100 \) m s\(^{-1}\), dipole tilt \( = 0 \), and particle "detector" altitude of \( 1.13 \) \( R_E \), which corresponds to DMSP spacecraft altitude. Except for the solar wind electron parameters, which will be discussed in the next section, these parameters are kept constant for all the subsequent plates discussed in this paper.

A comparison of Plate 1 and 2 shows that the model ions correspond closely with the real data, but the electrons do not. The model lacks the sharp gradient in electron flux which occurs just poleward of the cusp in the real data, so that in the mantle region and especially moving into the polar rain the simulated electron fluxes are much too high. Once into the polar rain, the actual data show only a slight gradient, significantly smaller than in the simulation (albeit the fluxes remain too high throughout because of the missing intense gradient near the mantle-cusp boundary). The model cusp begins at much higher magnetic latitudes than does the actual cusp; this long-standing problem, first pointed out by Burch [1973], continues to plague all existing magnetic field models. The resulting unrealistically high latitude for the cusp means

![Plate 1](image)

Plate 1. The spectrogram of the original Onsager et al. [1993] model. It shows that the electrons differential energy flux is too high in the mantle and polar rain regions. The spectrogram shows log differential energy flux, in units of eV cm\(^{-2}\) s sr eV, from 32 eV to 30 KeV, with the ion energy scale inverted. The lower of the two line plots shows the average energy in eV for the electrons (black) and ions (orange), and the top line plot is of integral energy flux in units eV cm\(^{-2}\) s sr.
Plate 2. The spectrogram of typical Defense Meteorological Satellite Program (DMSP) data. The spectrogram is taken from December 10, 1983, DMSP F7 data, which shows a typical cusp, mantle, and polar rain. The model tends to emulate this spectrogram. The cusp, the mantle, and the polar rain regions are labeled. See the caption of Plate 1 for the descriptions of the units, scale, etc.

that slight variations in the position from the intended trajectory correspond to apparently large changes in magnetic local time which cannot be taken seriously. In fact, the simulated local time in the sun-Earth plane is appropriate to the data presented in Plate 2 (the UT in the simulations has no significance).

Electrons have thermal speeds far exceeding the magnetosheath flow speed and therefore can enter the magnetosphere along open field lines across the polar cap. In contrast, ions have slower thermal speeds and therefore can only enter the magnetosphere from the regions in the magnetopause where the magnetosheath flow is subsonic [Reiff et al., 1977]. Several researchers have noted that there has to be a mechanism that limits the entry of electrons to balance the charge carried by ions and maintains charge quasi-neutrality in the ionospheric precipitating particle populations [e.g., Reiff et al., 1977; Burch, 1985; Lemaire and Scherer, 1978]. However, there are two possible interpretations to this mechanism. Both of them would limit the entry of the electrons, but they would produce different electron distributions in the ionosphere. The first method is to introduce a charge layer at the magnetopause. In this case, the electrons would lose energy as they cross the magnetopause, but those electrons that nonetheless made it across into the magnetosphere would regain the same energy as they travel into the magnetosphere. The second method is to maintain a potential drop between the magnetopause and the Earth. In this case, not only are low-energy electrons unable to reach the Earth but also electrons of all energies would suffer a net energy loss. We investigated both mechanisms. Plates 3 and 4 show the results of the first and second mechanism, respectively. It is very clear from the two plates that the second mechanism is the more realistic model in terms of modeling the observed spectrogram. When we discuss details of individual spectra from the mantle and the polar rain regions below, it will be shown that a net retarding potential is needed to fit the data. The solar wind and IMF configurations for Plate 4 (and Plate 3 since they both used the same input parameters) are discussed in the next section. They were chosen to simulate Plate 2, but they also are within realistic values.

The electric potentials employed in Plates 3 and 4 are derived computationally by a standard quick search algorithm which adjusts the potential for each field line until the density of ions and electrons are balanced for that field line. We also introduce a cap on the electric potential to prevent it from getting unrealistically high. The cap is needed perhaps, because the charge neutrality does not take into account the ionospheric sources of plasma. For the results that we present in Plates 4-6, we set the maximum potential to 250 V. This number was chosen to produce the spectrogram that is similar to the spectrogram in Plate 2, but it is also within the range of 0 - 400 V, which was found from fitting the spectra in Plate 2.

The plot of the potential of the spectrum in Plate 4 as a
function of time is shown in Figure 1. Because real data from spacecraft crossings are almost universally plotted at constant units of time rather than latitude, it facilitates a comparison with data to present the simulated crossing in the same format. The most equatorward points shown are the most recently merged field lines. Indeed, the merging is so recent that only a few ions can yet have reached the spacecraft altitude, and therefore a retarding potential exists to inhibit the electrons. This feature of the simulation corresponds to the region equatorward of the first arrow in Plate 4 and corresponds to the open field line LLBL near noon [Lyons et al., 1994]. In fact, the simulation results of a limited region with retarded electron entry and high-energy ion entry equatorward of the cusp (open field line LLBL) agree quite well with some published DMSP spectrograms [Newell et al., 1991, Plate 1; Newell and Meng, 1995, Plate 2].

Moving slightly poleward, the ions originate near the merging site but with enough elapsed time for the bulk of the magnetosheath population (accelerated by crossing the current layer) to have arrived. Since electrons can also enter the magnetosphere uninhibited, the result is that both ions and electrons maintain the same ratio and charge quasi-neutrality that they already have in the magnetosheath. Therefore, according to the simulation, very little or no potential is actually needed in the cusp. It should be pointed out that the work of Burch [1985] consisted of showing that the density of cusp electrons and ions was observationally the same: no evidence in the individual spectra was presented to indicate that a retarding potential is actually present. Figure 2 shows the plot of the differential energy flux versus energy of a typical cusp spectrum from DMSP data. The plot shows that the distribution for the cusp electron fits very well to an unretarded Maxwellian distribution, indicating that there is no population loss due to electric potential.

However, in Lemaire and Scherer [1978] cusp model, the cusp has field line potential of 25 V. Their model includes the ionospheric plasma which is absent in our model but their model does not include the effects of charged particles crossing the magnetopause current layer (which is strongly position dependent), the variation of the magnetosheath conditions with position, or magnetic field line convection. These effects are crucial to producing realistic spectra in the cusp (e.g., velocity filter effect or energy-latitude dispersion [Reiff et al., 1977; Onsager et al., 1993]), as well as in the mantle, the polar rain, and the open field line LLBL. Nonetheless, the Lemaire and Scherer [1978] model includes effects which we lack, most notably a treatment of the ionospheric plasma, which could be used to improve the results of our model. In effect, our approach includes the most important global variations, while the previous work included important local effects; an ideal model would incorporate the latter into the former.
3. Magnetosheath/Solar Wind Electrons

Although the electric potential helps reduce the entry of electrons in the mantle and the polar rain regions, it does not by itself give the correct signatures for those regions. Fairfield and Scudder [1985] showed that there are three components of the solar wind electron distribution function \( f \):

\[
f = f_c + f_h + f_s
\]

The core or thermal component, \( f_c \), accounts for 94% of the solar wind density and has the lowest temperature \( T_c \sim 1 \times 10^5 \) °K, with density \( n_c \sim 5 \text{ cm}^{-3} \) [Montgomery et al., 1968; Scudder and Olbert, 1979; Feldman et al., 1975]. Solar wind electrons also have a suprathermal component, traditionally called the halo component, \( f_h \), which has its origin in the solar corona, has \( T_h \sim 8 \times 10^5 \) °K, and \( n_h \sim 0.3 \text{ cm}^{-3} \) [Feldman et al., 1975, 1978]. The strahl component, \( f_s \), on the occasions where it is actually distinct from the halo, also has its origin in the solar corona and has the characteristics of high temperature \( T_s \sim 2 \times 10^6 \) °K, and low density \( n_s < 0.08 \text{ cm}^{-3} \), and is highly field aligned [Rosenbauer et al., 1976, Fairfield and Scudder, 1985]. All these numbers are just very rough estimates and are meant to give some feeling on the relative magnitude of the properties of each component. The strahl component may be taken simply as the high-energy tail of the halo component which, because of its higher energy, has not been scattered by coulomb collisions and therefore has not become isotropic [Fairfield and Scudder, 1985; Rosenbauer et al., 1976; Scudder and Olbert, 1979].

Since the precipitating particles originate from magnetosheath particles which in turn originate from solar wind, we investigated the model with one, two, and three solar wind components and found that in order to get realistic dayside electron distributions we need at least the halo in addition to the core component and occasionally all three components. The third one, strahl, frequently has density that is too low to be easily detected in the ionosphere, and as a result, often only two components are found. In order to illustrate the contribution of each component to the overall dayside spectrogram, we first show the spectrogram produced with just one component and then with two components.

Plate 5 shows the spectrogram if only the core solar wind electron component is included. The spectrogram is obtained with solar wind ion temperature of \( 1 \times 10^5 \) °K, electron temperature of \( 3 \times 10^4 \) °K, and density of 10 cm\(^{-3}\). These values are within valid ranges of solar wind core parameters [Feldman et al., 1978; Scudder and Olbert, 1979; Spreiter and Alksne, 1969]. The value of \( 3 \times 10^4 \) °K for electron temperature, although reasonable, is lower than average. This is necessary to compensate for an overly large computed heating in the magnetosheath, as we now explain. The density and temperature of the core electrons in the magnetosheath are obtained by inputting the corresponding solar wind values into the Spreiter and Sitdikov [1985] model, which gives the ratio of the upstream and downstream temperature of the combined ion and electron populations (a single fluid model). However, most heating in the magnetosheath occurs in the ions. Therefore the ratio overestimates the electron temperature in the sheath if a typical solar wind temperature is used. The rest of the input parameters are given in the beginning of the last section.
Plate 5 shows that the ions and the electrons of the cusp can be explained very well by the core component alone. The ion and electron total flux decreases with increasing latitude. The ions show the energy latitude dispersion [Reiff et al., 1977] or the velocity filter effect [Onsager et al., 1993] that is due to the motion along the magnetic field line and the E × B drift perpendicular to the field line. The lowest energy ions observable correspond to ions which originate from the merging site [Lockwood and Smith, 1992; Newhall and Meng, 1995]. This low-energy cutoff decreases with increasing latitude because of an increase in time elapsed since merging. Electrons do not show such a low-energy cutoff because of their high speeds. The highest energy component of each spectrum decreases with increasing latitude because of changing conditions in the magnetosheath and in the magnetopause current layer. Plate 5 shows that the core component of the solar wind can produce the cusp and mantle but not the polar rain. In fact, the core component is not detectable after ~1102:57 UT in Plate 5.

A comparison of Plates 1, 2, and 5 suggests that the polar rain electrons have to be hotter but less dense than the core component. Hotter electrons can overcome the parallel electric potential which the cooler core component cannot, and less dense electrons can give lower differential energy flux than the cusp and mantle spectra. For this reason, we added another component which has these properties to the solar wind input of the model. We experimented with various values of temperature and density while keeping the core component the same. It turns out that the temperature and density that give the best result are similar to those of the halo. Strahl-like temperatures would bring the electron spectrum high-energy cutoff to more than a few keV in the cusp, the mantle, and even the polar rain regions, which is higher than in the typical spectrogram (such cases do occur, however [Newhall and Meng, 1990]). The strahl-like densities would produce polar rain that has flux that is too low. The spectrogram in Plate 4 is obtained with the solar wind core electron $T_e = 3 \times 10^4$ K and $n_e = 10 \, \text{cm}^{-3}$, and magnetosheath halo electron $T_e = 1 \times 10^5$ K and $n_e = 0.25 \, \text{cm}^{-3}$.

The core (thermal) electron parameters given above are the values for those of solar wind which were inputted to the Spreiter and Suhara [1985] model as mentioned earlier. However, there is no such magnetosheath model for coronal (suprathermal) electrons. In the absence of such a model, we can only give the coronal electron properties in the magnetosheath which is where the precipitating particles originate and where the model computes the phase space density. However, Fairfield and Scudder [1985] found that the coronal electrons in the magnetotail lobe have similar characteristics to those in the solar wind in the vicinity of the ~1 AU region (e.g., no heating involved). In addition, we have fitted the polar rain spectra from the equatorwardmost part of the mantle region, as indicated by the second arrow in Plate 2, to the poleward edge region of polar rain (not shown in Plate 2) and found that the halo temperatures and densities do not vary much. The temperatures between these two large regions, approximately 10° in latitude, only range from $1.2 \times 10^6$ to $9.9 \times 10^5$ K, while the densities range from 0.3 to 0.2 cm$^{-3}$. The halo component in the mantle and polar rain regions covered in Plate 2 shows even less variation in density and almost the same variation in temperature. Thus, for simplicity, the model uses a constant halo temperature and density for all the magnetosheath halo electrons in Plate 4.

In a typical spectrogram, such as the one shown in Plate 2, there are only two components of the solar wind present, because the strahl component, as a result of its low density, gives phase space density that is below DMSP instrument threshold. In a few instances, when the strahl density is high, DMSP spectrograms and model spectrograms would reveal this component. Hardy et al. [1986] performed a statistical study of the characteristics of the polar cap precipitation with DMSP and found that there are two components to the polar rain electrons, but the second component which has higher temperature ($\geq 2.9 \times 10^6$ K) and lower density ($\leq 6 \times 10^4$ cm$^{-3}$) appears only 30% of the time. Their study also found that the ranges of values of density and temperature of the polar rain electrons are large, as indicated by the large standard deviations associated with these numbers (see, for example, their Figure 10), implying that there is a large variability of the properties of the solar wind coronal electrons. However, the first component of the polar rain, which appears in all cases, has temperatures in the $7.5 \times 10^5$ to $1.1 \times 10^6$ K range, which is also typical of the halo.

This variability of the properties of the solar coronal electrons may be partly the reason for the wide-ranging values of temperatures and densities attributed to the halo and the strahl components, making coronal electrons classification at low altitude somewhat difficult (see, for example, the numerous reported values at high altitude by Fairfield and Scudder [1985] and references therein, Hardy et al. [1986], Baker et al. [1987], Rosenbauer et al. [1976], and Feldman et al. [1975, 1978]). In the low-altitude polar rain studies, Hardy et al. [1986] classified their electrons as strahl having two components: high energy and low energy, while Baker et al. [1987] avoided this terminology altogether and instead classified the electrons as thermal and suprathermal. In the present paper, we adhere to the definitions of halo and strahl that are universally accepted, even by those researchers who reported different results for halo and strahl components: halo electrons have lower energies, lower temperatures, higher densities, and are more isotropic (but the isotropic information is not readily available at low-altitude observations), whereas strahl electrons have higher energies, higher temperatures, lower densities, and are more field aligned (e.g., Fairfield and Scudder, 1985). On the basis of these definitions, we call the second solar wind electron component for the model halo, because not only is the density high (0.25 cm$^{-3}$) but also the temperature is low ($1 \times 10^6$ K). Furthermore, the density is within the range of the halo density of 0.2-0.9 cm$^{-3}$ reported by Feldman et al. [1975], and the temperature is also within the range of halo temperature of $7.0 \times 10^5$ to $1.1 \times 10^6$ K reported by Feldman et al. [1975]. The next four sections summarize the morphology of the cusp, mantle, polar rain, and open field line LLBL.

4. Cusp Morphology

Plate 5 shows the spectrogram using the core component alone, whereas Plate 4 shows the spectrogram using the core and the halo components of the solar wind. The cusp in Plate 4 looks almost identical to that of Plate 5, indicating that the great majority of the cusp electrons and ions consist of the core component alone. The halo component is also present; however, as Plate 2 and 4 indicate, this is not easily seen or resolved from a typical DMSP spectrogram, because in the cusp region the core is much denser than the halo.
(approximately by a factor of 10-100), and the core and the halo components tend to occupy the same energy channels (< 1 keV). There are instances when the cusp spectrum could show a bimodal Maxwellian distribution of the core and the halo components, with the halo component occupying the higher-energy end of the spectrum when the halo component is unusually dense or when the halo temperature is unusually high. The evidence of the halo component can be seen more clearly when the differential energy flux of the spectrum is plotted individually, as is done in Figure 2 for one of the cusp electron spectra in Plate 2. Figure 2 shows that there are two components in the spectrum: the main component which has density of 40 cm\(^{-3}\) and temperature of 4.3x10\(^5\) K and another component at energies above 500 eV. The density and temperature given here are the fitted values for the spectrum, not the asymptotic or solar wind values, and are within the values of the core component of the dayside magnetosheath. The second component contains too few points to be fitted, but it has a higher temperature than the core, suggesting that it could be the halo component. At energies above 1.5 keV, the flux is at or below the instrument noise level, corresponding to one count at the detector channel.

The strahl component usually is not present, because its density is frequently too low in the ionosphere to be detected by the instruments (or at least to be resolved from the other components). Nonetheless, there are unusual cases when the density is high enough and in which case it may be possible to have trimodal Maxwellian distribution: core, halo, and strahl.

The core ion component shows the clear energy-latitude dispersion (Reiff et al., 1977; Otsager et al., 1993) which is often termed a “velocity filter effect”, although many other effects are also at work (e.g., the ion energy declines because of changing magnetosheath parameters and changing magnetopause current layer conditions and not because the entry region is restricted). In contrast, the core electron component shows a Maxwellian distribution to a very good approximation. At the higher energy end of the electron spectrum, there may be a higher-energy component of the halo Maxwellian distribution. The range of entry points of electrons observed in one single spectrum is quite small, less than 0.1 \(R_E\) and therefore the distribution can often closely approximate a single Maxwellian distribution, as demonstrated in Figure 2. The vast majority of the cusp ions and all cusp electrons come from the dayside magnetosheath (i.e., equatorward of the magnetic cusp). Equatorward of the second arrow in Plate 4, which is the model magnetic cusp, all ions and electrons originate from the dayside magnetosheath. Between the second and the third arrows in Plate 4, the portion of particle cusp that lies poleward of the magnetic cusp, only a small fraction of the ions, mainly the higher energy components, originate from within 1 \(R_E\) tailward of the magnetic cusp. Finally, one important characteristic of the particle cusp is that it is the region where there is little or no electric potential needed to maintain charge quasi-neutrality.

5. Mantle Morphology

Mantle ions consist of the core component of the solar wind, whereas mantle electrons consist of bimodal Maxwellian distribution of the core and the halo components, as indicated in Plates 4 and 5. The analysis of DMSP electron spectra in the mantle region confirms that this is indeed the case. Figure 3 shows the plot of the electron differential energy flux versus energy of a typical spectrum in the mantle region of Plate 2. It shows very clearly that the distribution has two components, one at lower energy and the other at higher energy. The lower-energy component has a temperature of 2.3x10\(^5\) K and a density of 35 cm\(^{-3}\), which are within the range of the core component of the dayside magnetosheath. The second component has a temperature of 1.2x10\(^6\) K and a density of 0.3 cm\(^{-3}\), which are also within the reasonable range of the halo component of the dayside magnetosheath. It should be noted that the temperatures and densities given here are the values of the magnetosheath electrons at the magnetopause entry points, not the asymptotic or solar wind values.

The fits of the two components in Figure 3 require a small electric potential of 5 eV, in accordance with Figure 1 which shows that the electric potential is zero or low at the equatorwardmost region of the mantle and rises to a maximum at the polewardmost region of the mantle (the mantle spectrum in Figure 3 comes from the equatorward region of the mantle in Plate 2).

All of the mantle electrons and the majority of mantle ions originate from the tail lobe or mantle regions in the magnetosheath. Only the lower-energy component of the ions at the equatorwardmost portion of the mantle, the portion of the mantle between the third and the fourth arrows in Plate 4, contains some ions that originate from the dayside magnetosheath. In the bulk of the ionospheric mantle signature (as identified by Newell et al., 1991), all ions originate from the high-altitude mantle. Similarly, all electrons in the mantle region originate from the high-altitude mantle.

Figure 3. The same as Figure 2 except that it is for a typical mantle electron spectrum from Plate 2. The plot shows that there are two components to the Maxwellian distribution, the core which occupies the lower-energy spectrum and the halo which occupies the higher-energy spectrum. The fitted magnetosheath core temperature is 2.3x10\(^5\) K and density is 35 cm\(^{-3}\), whereas the fitted magnetosheath halo temperature is 1.2x10\(^6\) K and density is 0.3 cm\(^{-3}\) (these are not the asymptotic values). Both Maxwellian fits require a small retarding potential of 5 V.
The mantle electron spectra approximate a Maxwellian distribution, albeit with a small low-energy cutoff due to the presence of a small electric potential in the mantle, more closely than do the cusp electron spectra, because the electrons in the mantle originate from regions that are tailward of the cusp entry points where the magnetosheath particles have more uniform temperatures and densities. Plate 4 shows that the spectrum for the halo electron component does not change much with latitude. In contrast, the total flux of the core for each spectrum (which can be seen more clearly in Plate 5) decreases rapidly with increasing latitude because of the constraints of the charge quasi-neutrality (the ion flux decreases with increasing latitude, as described in section 3). As a result, the poleward mantle region has more halo than core electrons, and the equatorward mantle region is just the reverse. The core component contributes to the higher-energy part of the spectrum, whereas the halo component contributes to the lower-flux at higher-energy component. For the rare cases when the strahl density is high, the mantle region may have a three-component Maxwellian distribution: core, halo, and strahl.

6. Polar Rain Morphology

The typical polar rain consists of the halo component of the solar wind. However, at the equatorward region of the polar rain, the lower-energy end of the spectrum may consist of the cusp electrons. These arc the core electrons shown poleward of the mantle in Plate 5. As with the cusp and the mantle, the strahl component would also be present in the polar rain when its density is high enough.

Baker et al. [1987] found there are two components of the polar rain: thermal and suprathermal, with the suprathermal electrons having densities of 0.04-0.26 cm\(^{-3}\) and temperatures of 8.5x10\(^5\)-1.5x10\(^6\) °K. Hardy et al. [1986] also reported two components, but both are suprathermal: the higher-density component, with temperature of 7.5x10\(^5\)-1.1x10\(^6\) °K, is always present, and the lower-density component, with temperature greater than 2.9x10\(^6\) °K, is only present 30% of the time in their 1400 spectra. We believe these differences could be explained by the locations of the polar rain spectra that they examined. Baker et al. [1987] might have examined their polar rain spectra from the equatorward polar rain regions (i.e., near the cusp or the mantle) where there are two components: core and halo. On the other hand, if Hardy et al. [1986] examined the polar rain mainly in the region away from the dayside oval, they would have observed only the halo component and occasionally the strahl component, when its density is high enough (apparently 30% of the time).

By and large the polar rain spectrum shows very little variation with latitude. The latitudinal variation, which is small, can be seen more clearly when the halo density is low and/or at the poleward region of the polar rain. Under this condition or at these locations, a small gradient in the polar rain exists such that the total flux decreases very slowly moving toward the nightside because of the increase in the tailward magnetosheath flow speed and the small decrease in halo density and temperature, approaching those of solar wind values, as the entry points move further down the tail [Torbert et al., 1981]. This effect is not shown in Plates 2 and 4, because the spectrograms do not extend far enough poleward. (In fact, the simple model of magnetosheath parameters currently used does not work beyond about \(x = -10 R_E\). Also, the halo density and temperature are kept constant in the model, as discussed in section 3).

An example of a typical fit of the polar rain spectrum is presented in Figure 4. It shows that the plot can be fitted with a Maxwellian with temperature of 9.9x10\(^5\) °K and density of 0.25 cm\(^{-3}\), which are the characteristics of the halo component. The temperature is within the range reported by Hardy et al. [1986]. The Maxwellian fit is very good, despite the fact that not all of the electrons come from the same entry points, because of the very uniform density and temperature of the magnetosheath electrons, which are approaching the solar wind values, in the tail regions. Figure 4 also shows that the Maxwellian is best fitted with a potential of 50 V. This potential is maintained roughly the same throughout the polar rain region in Plate 2, in agreement with Figure 1. The potential is required mainly to keep the core component from entering the magnetosphere in order to maintain charge quasi-neutrality. The majority of the suprathermal or coronal electrons (halo and strahl) can enter the magnetosphere despite of the potential because of their lower densities and higher temperatures. The coronal electrons have densities that are typically 10-1000 times lower than those of the core, and hence they do not contribute much to the overall electron density. Consequently, the electric potential rises mainly in response to the core electrons. The electric potential, which is effective at reaccelerating core electrons, can only retard the lower-energy component of the coronal electrons which have higher temperatures, allowing the majority of them to enter the magnetosphere. Since the magnetosheath flow, temperature, and density do not change much in the polar rain, the potential has to remain relatively constant in order for the polar rain spectra to show little variation, in accordance with observation and the spectra fits. However, the fitted value for the electric potential of 50 V in the polar rain is different from the 250 V obtained from the model. We
believe this discrepancy arises because the model does not have the correct convection model and magnetosheath model (as discussed earlier in section 3). A more realistic magnetosheath model would give a lower core electron density and temperature which in turn would require less potential to maintain charge quasi-neutrality. Moreover, the model does not take into account the magnetospheric and ionospheric particle populations which may contribute to the charge quasi-neutrality computation. The model shows that all of the electrons in the polar rain originate from tail lobes, as several observational studies have concluded [Fairfield and Scudder, 1985; Hardy et al., 1986; Baker et al., 1987].

The strahl component usually is not detectable by DMSP because of its low density but can be when the strahl density is high. The present paper only discusses the typical case (according to Hardy et al. [1986], the polar rain can be fitted by a single component 70% of the time), and therefore the strahl component is not shown in the spectrograms.

7. Open Field Line LLBL Morphology

The open field line portion of the LLBL is the region equatorward of the cusp (equatorward or left of arrow 1 in Plate 4) where the field lines are closest to the merging site. In this region, a few ions are present at the spacecraft altitude of 1.13 R$_E$ since most ions have not yet arrived. Therefore a potential drop is needed to limit the entry of the electrons which have higher speeds. An example of the LLBL spectrum is plotted in Figure 5, which shows that the Maxwellian fit requires a potential of 250 V. The Maxwellian fit in the open field line LLBL is not as good as that of other regions, because the magnetosheath plasma at the entry points for this region is changing more rapidly than elsewhere [see, for example, Spreiter and Stahara, 1985, Figure 10].

The electrons in the open field line LLBL can consist of the halo, the core, or the halo and core, depending on the density of the ions in the field line. At the equatorwardmost region of the open field line LLBL where no ions have yet arrived, a high potential is needed to keep most, if not all, core electrons from entering the magnetosphere. Consequently, only halo electrons are present. This situation is similar to the polar rain except that the potential is higher, because the magnetosheath core electrons have higher temperatures and densities on the dayside than in the tail. Farther poleward where some ions have reached, the potential

Plate 4. The model spectrogram that is produced with electric potential from the magnetopause to the Earth in order to maintain charge quasi-neutrality and the proper solar wind components as input. It shows the open field line portion of the LLBL, the cusp, the mantle, and the polar rain. The LLBL is the region equatorward (left) of arrow 1. (Arrow 1 is the leftmost arrow and arrow 5 is the rightmost arrow). The cusp is the region enclosed by the arrows 1 and 3. The mantle is in between the arrows 3 and 5. The polar rain is the region poleward (right) of the arrow 5. Arrow 2 indicates the latitude of the magnetic cusp. Arrow 4 is the line beyond which all ions in each spectrum originate from the magnetosheath in the tail lobe. Figure 1 gives the electric potential used to create the spectrogram. See the caption of Plate 1 for the descriptions of the units, scale, etc.
Plate 5. The spectrogram of just the core component of the solar wind. It shows that the cusp ions and electrons essentially consist of the core component of solar wind. Likewise, the mantle ions and the high-intensity part of the mantle electrons are due to the core component. However, the core component cannot produce polar rain electrons. See the caption of Plate 1 for the descriptions of the units, scale, etc.

Figure 5. The same as Figure 2, except that it is for an open field line LLBL spectrum. The plot shows that the open field line LLBL electrons can be fitted with the magnetosheath core component with a Maxwellian temperature of 6.4x10^5 °K, density of 55 cm^-3, and a potential of 250 V.

drops slightly, allowing some core electrons to enter. Thus the electron population consists of the core component at the lower-energy end and the halo component at the higher-energy end of the spectrum. Further poleward still, more ions enter the magnetosphere and the potential drops more accordingly to allow more core electrons to enter. It should be pointed out that the magnetosheath core electron temperatures on the dayside are much higher than those in the tail, and therefore it may be harder to resolve the halo component than, for example, in the mantle. This is illustrated in Figure 5, which shows an open field line LLBL can be fitted with a single Maxwellian component with temperature of 6.4x10^5 °K and density of 55 cm^-3, which are the characteristics of the dayside magnetosheath core electrons. Finally, at the polewardmost region of the open field line LLBL, at the boundary of the cusp and the LLBL, the potential drops to zero or almost zero, and the core component dominates the electron population, as described in section 4. The model, which caps the potential at 250 V, does not keep away all the core electrons, even at the equatorwardmost region, and thus the LLBL spectra shown in Plate 4 do not show the halo component prominently. Maintaining a constant cap potential works better for the polar rain than for the open field line LLBL, for the reasons described in the previous section. Like
in the cusp, the mantle, and the polar rain regions, the strahl component may be present in the high-energy end of the open field line LLBL spectra when it has higher density or temperature.

8. Range of Entry Points at the Magnetopause for a Single Spectrum

We have also examined the locations of the entry points of each spectrum in the model spectrogram. The plot of Δr of each spectrum in Plate 4 versus UT is shown in Figure 6. Δr is defined as the maximum distance between the magnetopause entry points of the lowest- and highest-energy ions with fluxes above the DMSP sensitivity threshold in each spectrum. The plot shows that within the particle cusp, the entry points of ions differ by at most ~3 R_E, while in the mantle the difference is of the order of 4 R_E. The Δr for electrons is even smaller than those for ions, < 0.1 R_E, as it must be in order for the cusp electrons to fit well to a single Maxwellian distribution (as observed).

The original conception of cusp ion entry [Rosenbauer et al., 1975] was that of a simple velocity filter effect, with a narrow low-latitude injection point. In this conception, the ions precipitating farther poleward in the cusp, and throughout the mantle, are simply the low-energy ions injected at the merging point whose time of flight delayed precipitation. Newell et al. [1991] argued that because such mantle precipitation signatures are seen poleward of the auroral oval over much of the dayside ionosphere, the entry region must be much more extended than just the dayside ionosphere below the magnetic cusp. The present simulations clearly show that most mantle ions do indeed originate poleward of the magnetic cusp, that is, from the high-altitude mantle region.

9. Summary and Conclusions

This paper shows that a quantitative model based on Onsager et al. [1993], but with improvements in two key areas, namely the constraint of charge quasi-neutrality and the addition of coronal electrons to the solar wind, can simulate the dayside ion and electron precipitation fairly accurately. All dayside precipitation which is on open field lines can be modeled with a single continuous entry mechanism. The differences in the magnetopause entry points, the charge quasi-neutrality constraints, and the ratios of the three solar wind components in the precipitating particles give rise to four distinct regions in the ionosphere, namely the open field line portion of the LLBL, the cusp, the mantle, and the polar rain.

The typical cusp electrons and ions consist mainly of the solar wind core component, but the higher-energy part of the electron spectrum may contain the halo component. The polar rain electrons consist mainly of the halo component. In the region poleward of the cusp and the portion of the polar rain closest to the dayside oval, around and including the mantle region, there are typically two electron populations: the core component at lower energies and the halo component at higher energies. The open field line LLBL is harder to fit, partly because of the magnetosheath conditions which are changing very quickly at the entry points. The electron composition in this region consists of the core, or the halo, or the center and the halo. When the strahl density or temperature is higher than usual, it can be seen in the electron spectra as well.

The model shows that a potential drop between the magnetopause and the Earth works better than a charge layer on the magnetopause. It turns out a small, or no, electric potential is needed in the cusp, because the ions and electrons have already maintained charge quasi-neutrality in the magnetosheath and they both can enter the magnetosphere freely. The potential then increases, throughout the mantle region up to a threshold value, typically up to 100 or 200 V, in the polar rain region. In the polar rain region, the coronal or suprathermal electrons, because of their low densities and high temperatures, are not completely repelled by the electric potential and continue to enter the magnetosphere, albeit without their low-energy components. The potential in the open field line portion of the LLBL varies from a low to a very high value, higher than that of polar rain. Table 1 summarizes the electric potential and other characteristics of open field dayside particle precipitation regions. Because of the space limitation, much of the information has been simplified and some has been omitted. Sections 4–8 give a more complete and better description of each region.

Although there has been no statistical study done on the retarding electric field in the polar rain, the potential obtained by the model is a bit higher than a few sample cases we have tried, perhaps because of the fact that the model does not take into account the magnetospheric/ionospheric particles. Furthermore, the model can be improved with the introduction of a more realistic ionospheric convection pattern, magnetosheath model, and a better magnetic field model. One common and persistent problem with all published existing magnetic field models is that the location of the magnetic cusp being at a much higher latitude than the actual cusp [Burch, 1973], as described in section 2. Nonetheless, the model has been invaluable in clarifying the general behavior of the LLBL, the cusp, the mantle, and the polar rain.
<table>
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<th>Polar Rain</th>
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* the maximum distance of the magnetopause entry points of the ions or electrons in each spectrum.
† location of all the magnetopause entry points for the region.
‡ threshold < a few hundreds V

as a function of solar wind properties, and in determining their entry points into the magnetopause.

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