ELECTRON DENSITY DISTRIBUTIONS IN THE HIGH-LATITUDE MAGNETOSPHERE

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ABSTRACT

Electric field spectrum measurements from the plasma wave instrument on Dynamics Explorer 1 are used to study the local electron density at high altitudes in the polar cap and nightside auroral zone. The electron density is derived from the upper cutoff of the whistler-mode auroral hiss emissions at the electron plasma frequency. In the nightside auroral zone, sharply defined regions of low electron densities are commonly found to occur. Electron densities in these regions are strongly depleted in relation to the adjacent plasmaspheric and polar densities, forming a low density cavity at 70° ± 5° invariant latitude. A comparison of these density depletions with simultaneous particle measurements indicates a correspondence between low auroral plasma densities, upflowing ion distributions and an energetic precipitating electron population. These correlations show that density depletions in the nightside auroral zone are directly associated with auroral acceleration processes. Inside the polar cap, density values are found to vary inversely with increasing radial distance, falling by more than two orders of magnitude over an altitude range of 1.75–4.66 Re. The observed variation indicates a power law distribution of densities, consistent with a steady-state radial outflow of ionospheric plasma along polar magnetic field lines.

ELECTRON DENSITIES DERIVED FROM WAVE PROPAGATION EFFECTS

High-altitude electron density profiles above the F region, derived from density measurements based on wave propagation effects, were obtained by the topside sounder satellites of the 1960s and early 1970s. Electron densities were derived from the observed plasma resonances which were excited by sounder-transmitted radio-frequency pulses (see references cited in /1/ and /2/). Decades later, a technique for deriving the electron density from the propagation of whistler mode waves in the magnetosphere was used to determine the existence of a plasma cavity in the nightside auroral zone, using electric field spectrum measurements from the Hawkeye spacecraft /3/. This technique has been subsequently refined and employed to statistically examine the electron density profile in the polar cap /1/ and to explore the auroral plasma cavity below ~1.7 Re /2/, using plasma wave data from Dynamics Explorer 1.

Electron density values at polar and auroral latitudes are obtained from an analysis of whistler mode wave propagation using electric field spectrum measurements from the plasma wave instrument (PWI) on Dynamics Explorer 1. This instrument has been described in detail in a previous report /4/. Spectrograms obtained from the electric and magnetic field amplitude measurements illustrate broadband electromagnetic auroral hiss emissions propagating below the electron cyclotron frequency in the auroral zone and polar cap /5/. The auroral hiss is expected to be propagating in the whistler mode because the whistler mode is the only electromagnetic mode which can propagate in this frequency range /6/. Since auroral hiss is a whistler mode emission, this radiation, when propagating parallel to the magnetic field, has a characteristic upper frequency cutoff at either the electron cyclotron frequency or the electron plasma frequency, whichever is smaller (see Figure 3-2 in /7/). In the low density regions of the polar cap and auroral zone, parallel-propagating whistler mode waves will resonate at the local electron plasma frequency and a sharp upper frequency cutoff.
will be evident on the electric field spectrogram. This upper frequency cutoff of the auroral hiss can be digitized and the electron density can be calculated from the plasma frequency by using the relation \( n_e = (f_{pe}/9)^2 \), where \( n_e \) is in cm\(^{-3}\) and \( f_{pe} \) is in kHz. The technique of using the upper frequency cutoff of the auroral hiss emissions to derive electron densities is based on the assumption that the whistler mode wave is propagating at very small angles to the magnetic field at resonance. The angle of the hiss propagation with respect to the magnetic field has been quantitatively measured. Typically near the upper frequency cutoff, the hiss emissions have been found to be propagating at small angles to the magnetic field, introducing a maximum error of \( \pm 30\% \) in the density determination for waves propagating up to \( 20^\circ \) off the magnetic field line \(/2/\). This density analysis technique and its limitations have been fully described in an earlier report \(/2/\).

The determination of the electron density from the electron plasma frequency cutoff of the hiss emissions is a valuable method of determining the total plasma density and is independent of the energies of the plasma population. The technique permits the determination of the density to a high degree of accuracy, limited primarily by the size of the discrete frequency steps of the plasma wave instrument \(/4/\). Inside the polar cap, the uncertainty in the density determination is typically \( \pm 13\% \) \(/1/\). The uncertainty in the determination of auroral electron densities increases to \( \pm 27\% \), due to the presence of competing wave modes propagating in the 1-100 kHz frequency range at auroral latitudes and to the increased probability of hot plasma effects which can cause the whistler mode to be strongly attenuated at frequencies below the electron plasma frequency \(/2/\). No density values have been calculated with an uncertainty exceeding \( 40\% \).

**THE AURORAL HISS SIGNATURE IN THE PLASMA WAVE DATA**

Auroral hiss emissions are generated on nightside auroral field lines below 2 R\(e \) \(/5/\). The characteristic funnel shaped of the hiss emissions is the result of the upward propagation of these whistler mode waves above the source region (see Figures 10 and 11 in \(/5/\)). The hiss emissions are not confined to the auroral zone but spread out over a wide range of latitudes both poleward and equatorward of the source field lines. Hiss emissions, which are also found in the dayside auroral zone, will frequently exhibit a latitudinal asymmetry in the direction of the pole, resulting in a nearly continuous band of emissions over the polar cap. Poleward of the auroral zone the whistler mode waves are driven into resonance at a sharp upper frequency cutoff, identified as the electron plasma frequency \(/1/\). Equatorward of the source field lines the whistler mode wave propagates at large angles to the magnetic field lines, resulting in a poorly defined upper frequency cutoff. In this region the hiss emissions will not resonate at the local electron plasma frequency (see Figure 2 in \(/2/\)).

Directly above the source region the propagation of the whistler mode emissions into a region of field-aligned diminished plasma densities produces the characteristic appearance of the auroral cavity in the PWI data.

A typical spectrogram, for November 19, 1981, is shown to illustrate the auroral hiss signature in the plasma wave data (Figure 1). Below 20 kHz, the characteristic funnel-shaped hiss emissions can be seen propagating poleward from the nightside auroral region, with wave intensity diminishing as the waves propagate to higher latitudes deep inside the polar cap. Z mode radiation, found both inside and poleward of the cavity, can be seen up to the electron cyclotron frequency and intense auroral kilometric radiation is found above 90 kHz over the polar cap and auroral zone. From 1900-1930 UT these intense AKR emissions saturate the fourth band of the plasma wave receiver, producing an artificial cutoff at 56 kHz. The Kp index for this pass is 3.

The spacecraft is approaching the auroral zone from the nightside polar cap in the northern hemisphere. The electron density profile in the polar cap, derived from the electron plasma frequency cutoff, is relatively smooth in comparison to the irregular cavity profile. The polar cap densities vary between 3 cm\(^{-3}\) and 5 cm\(^{-3}\). At 1941 UT the spacecraft encounters a region of slightly diminished plasma densities, followed by a steep gradient in the density profile at 1945 UT when it encounters the main auroral plasma cavity. Sharp spikelike features at 1941 and 1945 UT are impulsive intensifications in the wave activity which have no observable magnetic component. These electrostatic bursts periodically obscure the whistler mode cutoff throughout the auroral zone crossing. Just poleward of the main auroral cavity (1939-1940 UT) the average electron density is 4.2 cm\(^{-3}\). At 1941 UT the electron density falls below 3 cm\(^{-3}\) and remains relatively constant until the main cavity is encountered at 1945 UT when the density drops to 0.4 cm\(^{-3}\). The minimum cavity density of 0.17 cm\(^{-3}\) occurs at 1946 UT, more than an order of magnitude lower than the average polar cap density values just poleward of the cavity \(/2/\). The auroral density profile becomes irregular after 1947 UT, and the simultaneous occurrence of electrostatic bursts and Z mode radiation in the same frequency range makes it difficult to trace the whistler mode cutoff continuously in this interval. However, there is no indication of an increase in the density profile prior to 1953 UT when the auroral hiss emissions and the upper frequency cutoff are obscured by intense, impulsive electrostatic bursts. The last measured density value in the
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Fig. 1. A representative spectrogram of electric field amplitude measurements illustrating a pass through the nightside polar cap and auroral zone in the northern hemisphere on November 19, 1981. The trajectory of the spacecraft in a magnetic meridian plane is shown in the lower left-hand corner. The poleward edge of the auroral plasma cavity occurs at 19115 UT (from /2/).

A region of sharply depleted plasma densities with well-defined poleward edges is a common occurrence on nightside auroral field lines in the PWI data /2/. Seventy-four examples of auroral density depletions from the PWI data, covering the interval of September 1981 through April 1982, were selected to examine the location of the auroral plasma cavity under varying conditions of magnetic activity and to determine the depth of the density depletion. The plots in Figure 2 illustrate the location of the auroral cavity for Kp < 3 and Kp ≥ 3. For quiet conditions (Kp < 3), 71% of the auroral cavities have poleward edges at invariant latitudes greater than 72°. For more disturbed times (Kp ≥ 3), 71% of the auroral cavities have poleward edges at invariant latitudes below 72°. No cavity data were available with a Kp index greater than 6. These results are consistent with the expansion of the polar cap and auroral oval in times of increasing geomagnetic activity. Minimum densities inside these cavity regions are typically found to vary from 0.1 cm⁻³ to 14 cm⁻³ over the entire range of DE altitudes with no strong dependence on magnetic activity or on altitude /2/.

Since the auroral cavity is a common occurrence on nightside auroral field lines, the mechanism responsible for the depletion of plasma on these field lines will also be a common auroral phenomenon, subject to the same geomagnetic influences. The most likely mechanism for the transport of auroral plasma is the parallel electric field which accelerates the precipitating electrons and the upflowing ions, frequently observed on auroral field lines /9,10,11/. A typical auroral zone signature in the ion data is a broad angular distribution of low energy ions at the edges of a region of keV upward ion acceleration /12/. Statistical studies of energetic auroral ions have shown that upflowing H⁺ and O⁺ ions with energies above 1 keV are commonly found at auroral latitudes and that these ion events exhibit the same latitudinal variations with changes in geomagnetic activity as the auroral plasma cavity /11/. Upward directed parallel electric fields of 15 mV/m or less have been correlated with these upward directed ion beams and with the auroral plasma density depletions just above 2 Rg /13,14/.

A statistical comparison between the occurrence of upflowing auroral ions and auroral density depletions found a positive correlation between upflowing ions with energies...
Fig. 2. The DE orbit traces are plotted for 74 cavity intervals as a function of magnetic latitude and geocentric radial distance for Kp<3 and for Kp>3. Four representative field lines at invariant latitudes of 65°, 70°, 75°, and 80° are indicated on each plot. The average location of the auroral cavity is 70° ± 5° invariant latitude. The equatorward shift of the cavity with increasing geomagnetic activity is evident (from /2/).

DE 1 observations from the high-altitude plasma instrument (HAPI), the retarding ion mass spectrometer (RIMS) and the energetic ion composition spectrometer (EICS) are shown to determine the distribution and energies of the auroral ions and electrons inside the auroral cavity. The instruments are fully described in /15,16/ and /17/, respectively. The density profile, corresponding to the pass through the nightside polar cap and auroral zone illustrated in Figure 1, is shown in the bottom panel of Figure 3. Dashed lines connect density data points separated by data gaps lasting more than 32 seconds. The HAPI data in the top panel of Figure 3 shows the development of a very energetic (10 keV) precipitating electron population during the 19111-19145 UT interval, an interval when the electron density falls by 30% below the average polar cap density values immediately poleward of the auroral zone. After 19145 UT the auroral electron population becomes slightly more energetic, with peak energies of nearly 20 keV occurring inside the cavity interval. These energetic precipitating electrons are present throughout most of the cavity interval. However, minimum cavity densities coincide with a temporary disappearance of this energetic downward flux of auroral electrons (1946-1947 UT).

Fig. 3. The precipitating electron energy flux and the electron density profile corresponding to the auroral zone crossing illustrated in Figure 1. The precipitating electron population exhibits an increase in energy flux which coincides with a modest density depletion preceding the main cavity at 1941 UT. Electrons with peak energies of nearly 20 keV are found inside the auroral cavity. Peak electron energy fluxes at 1941 UT are greater than 10^{-4} ergs/cm^2-s-sr-ev.
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LOW ENERGY IONS IN THE AURORAL PLASMA CAVITY

Fig. 4. The low energy (<250 eV) H\(^+\) and (<50 eV) O\(^+\) ion distributions for the auroral zone crossing illustrated in Figure 1. An intense H\(^+\) conic distribution at 1941 UT coincides with the modest density depletion preceding the onset of the main cavity. A weak field-aligned H\(^+\) beam correlates with the onset of the auroral plasma cavity at 1945 UT.

Figure 4 shows the distribution of low energy H\(^+\) and O\(^+\) ions for this auroral zone crossing. During the 4-minute interval preceding the onset of the main cavity, the RIMS instrument shows an intense flux of low energy H\(^+\) ions with a very broad angular distribution, as well as a weaker flux of O\(^+\) ions with a broad angular distribution. At 1945 UT, when the spacecraft encounters the auroral plasma cavity, a weak field-aligned H\(^+\) beam is indicated in the RIMS data. The onset of a cold rammed distribution of O\(^+\) at 2003 UT indicates the plasmapause region.

Much of the ion activity in this cavity interval occurs in the EICS data (Figure 5). Weak low-energy O\(^+\) conic and beam distributions (Figure 5, panel 3) parallel the low-energy H\(^+\) distributions in panel 1, but the O\(^+\) integral flux is substantially lower and the upflowing O\(^+\) ion distribution does not persist throughout the cavity interval. A weak (<1 keV) H\(^+\) conic distribution occurs poleward of the main cavity (1941-1945 UT) and collapses to a field-aligned beam at 1945 UT. This low energy H\(^+\) beam correlates with the onset of the auroral cavity and is evident throughout the cavity interval until 1956 UT (panel 1). The energetic (>1 keV) ions (panels 2 and 4) also exhibit a beamlike distribution inside the auroral cavity but these beams do not correlate with the poleward edge of the cavity at 1945 UT. Although highly energetic ion beams are frequently found inside the auroral plasma cavity, it is the (<1 keV) H\(^+\) beams which strongly correlate with the onset of the plasma cavity /2/.

USING THE AURORAL HISS RESONANCE TO STUDY ELECTRON DENSITIES IN THE POLAR CAP

The auroral density profile inside the plasma cavity is highly variable with density fluctuations of a half order of magnitude or more occurring on time scales of tens of seconds /2/. Poleward of the cavity, the density profile is typically smoothly varying. Polar cap densities generally tend to exceed the minimum densities found inside the cavity by nearly an order of magnitude /2/ and will vary inversely with increasing radial distance /1/. Low-altitude measurements of polar electron densities found that the region poleward of the auroral zone is a stable region of open field lines and depressed electron densities /18,19/. The polar pass illustrated in Figure 1 is a good example of a smoothly varying polar density profile. However, this is not consistently true for all polar passes (see Figures 7 and 8 in /1/). An examination of individual polar passes shows large variations in electron density from orbit to orbit as well as substantial temporal/spatial density variations on individual passes, seen in Figure 1 from 1903-1912 UT.
Fig. 5. H+ and O+ pitch angle distributions corresponding to the auroral cavity illustrated in Figure 1 are shown for two energy bins. Low energy (<1 keV) field-aligned H+ beams are correlated with the onset of the cavity at 1945 UT and energetic (1-17 keV) H+ and O+ beams are found deep inside the plasma cavity.

To examine the variation in electron density as a function of increasing altitude in the polar cap, the electron plasma frequency was numerically determined from an analysis of 153 spectrograms, selected from the 8-month interval of September 1981 through April 1982. During this period, the geocentric radial distance of DE 1 in the polar cap region varied from 1.6 Re to 4.7 Re or from 4000 km to 23000 km above the earth's surface. In order to eliminate all auroral electron densities from the statistical study, the polar cap region was defined for invariant latitudes of 80° or more (see Figure 2). Figure 6 is a semilog plot of the calculated electron number density as a function of radial distance for nearly 11,000 density values. The plot shows that a wide scatter exists in the electron density for a given radial distance. In addition to the scatter expected from the observed variations in the density profile over relatively short time periods, the scatter could also be due to variations in the latitudinal position of the spacecraft within the polar cap, as well as local time variations. Despite the wide spread in electron density values at a given radial distance the electron density clearly exhibits a decrease with increasing radial distance, expected in this polar region of radially outflowing ionospheric plasma.

The apparent upper density cutoff evident in Figure 6 above 3 Re corresponds to the electron cyclotron frequency. This upper density cutoff occurs because the electron density can be determined from the whistler mode cutoff frequency only when the electron plasma frequency is lower than the electron cyclotron frequency. When the auroral hiss propagates into a region of higher polar densities where the electron plasma frequency approaches or exceeds the electron cyclotron frequency, the electron density calculated from the apparent upper frequency cutoff of the hiss emissions merely represents a lower limit on the actual electron density. A statistical tabulation of the data points for which the upper frequency cutoff was greater than 60% of the electron cyclotron frequency indicated that cyclotron resonance contaminated the determination of the electron density in less than 1% of the cases below 3.5 Re, increasing to about 4% of the cases for radial distances above 4.25 Re. A total of 2.7% of all density values are affected.

To further explore the relationship between electron density and radial distance and to determine the spread in density values for a given altitude, the radial range was divided into radial increments of 0.25 Re and the median value of the electron density was computed for each radial increment. All cutoff frequencies were used in calculating the median
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Fig. 6. A scatter plot of electron density in the polar cap as a function of radial distance. The large scatter in the data is mainly due to temporal, latitudinal and local time variations in the polar cap density profile.

Values, even when the cutoff is determined by the electron cyclotron frequency. Median values were chosen, rather than average values, to eliminate the effect of electron plasma frequencies near or greater than the electron cyclotron frequency. Since the medians are, in all cases, well below the electron cyclotron frequency, median values are not affected by the cyclotron resonance effect. Figure 7 is a log-log plot of the median electron density as a function of radial distance. The error bars indicate quartiles, which show the spread in 25% of the data above and below the median values. Median number densities range from 100 cm$^{-3}$ at 1.75 RE to 0.4 cm$^{-3}$ at 4.5 RE. A straight line provides a good fit through the median points, suggesting a power law relationship between the electron density and the radial distance. The slope of the best fit through the points indicates a power law exponent of $-5.34 \pm 0.42$.

The polar cap is a region of upward, field-aligned fluxes of light ionospheric ions, as well as occasional fluxes of heavier ions. The conservation of ion flux in the magnetic flux tube, the condition of electrical neutrality in the polar cap region, and the continuity equation for the radial outflow of plasma in the polar magnetosphere can be used to show that $n_e \propto u^{-1} R^{-3}$ where $R$ is the cross-sectional area of the flux tube and $u$ is the plasma flow velocity parallel to the magnetic field /1/. Because of the pressure gradient between the ionosphere and the magnetotail, the plasma flow velocity can be expected to increase with increasing radial distance. If a valid power law relationship exists between the electron number density and radial distance, then $n_e \propto R^{-\alpha}$ where $\alpha = 3$. The exponent in Figure 7 then is consistent with the expected relationships of radial distance with flow velocity and cross-sectional area in the polar cap. The data indicates that the plasma flow velocity increases approximately with increasing radial distance as $R^2$.

The exponent derived from the best line fit through the median density data points in Figure 7 is significantly greater than the exponent of 3.85 derived in an earlier study, although the median density values above 2.5 RE are consistent with the earlier values /1/. The extension of the density data base to lower altitudes with the inclusion of density data from the spring of 1982 is primarily responsible for the observed increase in the exponent of the power law relationship and the improved correlation between the electron density and radial distance. These low-altitude densities are consistent with the anticipated increase in the electron number density below 2 RE (see Figure 12 in /1/).
Fig. 7. A log-log plot of median number density as a function of radial distance. The best line fit through these points indicates a power law distribution for electron densities in the polar cap.

**SUMMARY**

Electron density profiles, derived from the upper frequency cutoff of the auroral hiss emissions, have been constructed to study plasma density depletions in the nightside auroral zone and density variations with increasing altitude in the polar cap. Sharply defined regions of depleted plasma densities are commonly observed on nightside auroral field lines in the DE 1 plasma wave data. Electron densities in these regions are strongly depleted in relation to the adjacent plasmaspheric and polar densities, forming a low density cavity at 70° ± 5° invariant latitude. The location of the poleward edge of the auroral cavity responds to changes in magnetic activity, occurring at high invariant latitudes above 72° for low Kp values (Kp<3) and moving to lower invariant latitudes at times of higher geomagnetic activity (Kp≥3). Minimum densities inside the auroral plasma cavity are found to vary from 0.1 cm⁻³ to 4.0 cm⁻³ over the entire range of DE altitudes (2-4.7 RE).

A comparison of auroral density depletions with simultaneous particle measurements indicates a correspondence between low auroral plasma densities, upflowing ion distributions and an energetic precipitating electron population. Increases in the energy flux of precipitating auroral electrons has been found in regions of depleted auroral plasma densities. Low energy (<1 keV) H⁺ beams are strongly correlated with the poleward edge of the auroral cavity and are found to persist throughout the cavity interval. Energetic (>1 keV) ion beams are found inside the auroral plasma cavity in the region of lowest auroral plasma densities but these upflowing ions do not correlate with the onset of the plasma cavity. The parallel electric field, which drives the auroral ion beams, appears to be the most efficient mechanism for the transport of ionospheric plasma and the creation of auroral density depletions.

Poleward of the auroral zone, the densities are typically an order of magnitude higher than the minimum densities found inside the auroral plasma cavity. A statistical survey of electron densities in the polar cap indicates that polar densities vary inversely with increasing radial distance, falling by more than two orders of magnitude over an altitude range of 1.75-4.66 RE. The observed density variation indicates a power law distribution of densities, varying as R⁻5.34 ± 0.42. This power law distribution is consistent with a steady state, radial outflow of ionospheric ions and electrons along polar magnetic field lines and implies that the plasma flow velocity varies approximately as R² above 1.75 RE.
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