Ion Heating by Broadband Low-Frequency Waves in the Cusp/Cleft


Ion conic distributions are often observed in the cusp/cleft region of the dayside magnetosphere. We show that these ions can be heated via the process of cyclotron resonance with broadband low-frequency (near the ion gyrofrequency) waves. Data from two cusp/cleft crossings of the polar-orbiting DE 1 satellite are studied in detail. There is very good agreement between the onset of low-frequency waves and the onset of ion heating. Observed cool O⁺ distributions and observed wave intensities from one orbit are used as input to a Monte Carlo simulation. Given the assumptions underlying the simulation model, the resulting hot O⁺ distributions are in good agreement with the corresponding observed distributions. We explore this agreement using a further simplified analytic model which accounts for much of the agreement and many of the discrepancies. The mean ion energies of about 200 eV obtained from the simulation agree well with several minutes of observations, corresponding to a distance of nearly 1000 km along the satellite orbit. The O⁺ distribution functions from both simulation and observations show that heating near the equatorward edge of the cusp/cleft region is rather local, while ions observed well inside this region may be heated over altitudes of several thousand kilometers. This resonant heating by broadband low-frequency waves is important for the outflow of ionospheric ions into the magnetosphere.

1. INTRODUCTION

It is well known that ions in the ionosphere and magnetosphere can be heated perpendicularly to the geomagnetic field. These ions may then move adiabatically up the field lines of the inhomogeneous terrestrial magnetic field and form so-called conics in velocity space. These distributions are observed by rockets at altitudes of a few hundred kilometers [e.g., Whalen et al., 1978; Kintner et al., 1989] and by satellites up to many thousand kilometers [e.g., Sharp et al., 1977; Klumpar, 1979; Gorney et al., 1981; Yau et al., 1984, 1985a,b; Hultqvist et al., 1988; Lundin et al., 1990]. It is now established that ions of ionospheric origin can be heated and contribute significantly to the magnetospheric low-frequency waves can cause significant ion heating in the ion heating mechanism(s) has (have) been an area of extensive research during the last few years [Klumpar, 1986 and references therein]. Most suggested mechanisms include interaction with waves, e.g., emissions near the lower hybrid frequency [Chang and Coppi, 1981] or above the ion gyrofrequency [Ungstrup et al., 1979; Ashour-Abdalla and Okuda, 1984]. Other theories suggest heating by broadband waves near the ion gyrofrequency [Chang et al., 1986; Crew and Chang, 1990] or by emissions below this gyrofrequency [Temerin and Roth, 1986; Ball, 1989], but, for example, acceleration also by double layers is possible [Borovsky, 1984]. It should be noted that more than one major ion energization mechanism may be operating. For example, the ion conics observed by rockets are not necessarily heated in the same way as conics observed at much higher altitudes. The most successful comparisons of observed and theoretically modeled ion conics are related to observations in the central plasma sheet [Retterer et al., 1987a] and in the auroral zone [Crew et al., 1990], where broadband low-frequency (near the ion gyrofrequency) waves seem to cause the ion energization. In the present report we show that similar low-frequency waves can cause significant ion heating in the cusp/cleft region.

The cusp/cleft is a region of the dayside high-latitude magnetosphere, extending from less than 0900 to more than 1500 magnetic local time and with a latitudinal width of a few degrees. Most of this region is often called the cleft, while the cusp is more localized around noon. For our purposes the cusp may be regarded as a subset of the cleft. However, since the nomenclature is not well established and since the boundaries between the cusp, the cleft, and other subregions are still under investigation [Heikkila, 1985; Lundin, 1988; Newell and Meng, 1988], we choose to discuss a loosely defined cusp/cleft region. In this region, precipitation of shocked solar wind (magnetosheath) plasma usually occurs. Magnetosheath electrons and ions typically have energies of 100 eV and 1 keV, respectively, and in the cusp/cleft these particles have more or less direct access to low altitudes. Low-frequency broadband waves are also common in this region [Gurnett and Frank, 1978; Erlandson et al., 1988]. Part of the cusp/cleft appears to be an open flux tube connected to the magnetosheath, while some field lines may connect to the low-latitude boundary layer.

The cusp/cleft region is known to be an important source of upwelling O⁺ ions [Lockwood et al., 1985a,b; Thelin et al., 1990]; these ions make a significant contribution to the magnetospheric plasma [Chappell, 1988]. The relatively low velocities of upwelling ions (tens of kilometers per second) and...
the latitudinal motion of the cusp/cleft region may give rise to a large-scale presence of relatively cool $O^+$ ions at high altitudes (geocentric distance of 3 - 4 Earth radii) near noon in the high-latitude magnetosphere. Many mechanisms may in principle heat the $O^+$ ions [Moore et al., 1986]. However, we shall show here that strong evidence is accumulating for the notion that cyclotron resonance heating by broadband low-frequency waves near the ion gyrofrequency is responsible for much of this energization. Results from the Viking satellite obtained at a geocentric distance of about 3 $R_E$ (Earth radii) reveal intense heating of upflowing ions near the equatorward edge of the cusp/cleft in addition to the ion heating in the region of more dense magnetosheath plasma [André et al., 1988]. All this ion heating is closely associated with broadband waves in the range of the ion gyrofrequencies. Assuming the ions to be $O^+$, ion heating theory [Chang et al., 1986] can be used to show that observed electric field waves can produce a locally heated ion distribution (90ø conic) observed close to the equatorward edge of the cusp/cleft [André et al., 1988]. Local ion heating at high altitudes is possible since there is a sharp spatial gradient in wave intensity near the equatorward edge of the cusp/cleft. Thus ions which drift poleward into the cusp/cleft due to high-latitude $E \times B$ convection experience a sudden onset of broadband waves. Similar events have been observed at higher altitudes by the DE 1 satellite [Peterson et al., 1989]. Here mass spectrometer data are available, and again estimates show that the observed broadband waves can generate $O^+$ ion distributions observed close to the equatorward edge of the cusp/cleft. In the following we investigate two DE 1 events in detail. We extend the previous studies by using a Monte Carlo simulation [Retterer et al., 1983, 1987a] to estimate $O^+$ ion heating not only near the equatorward edge but also inside the cusp/cleft. These simulation results are compared with an analytic model. Furthermore, we use magnetometer data to investigate the polarization of the waves. In this report we concentrate on ion heating via a cyclotron resonance process involving waves near the ion gyrofrequency. The details of heating by double-cyclotron absorption of waves at roughly half the gyrofrequency have also been considered [Ball and André, 1990]. Our conclusion is that cyclotron resonance heating by broadband low-frequency waves can cause a major part of the ion heating observed in the cusp/cleft.

2. Observations

A sketch showing a satellite moving poleward into the cusp/cleft region is shown in Figure 1. Here region A is the cusp/cleft with rather intense broadband low-frequency waves (shaded), and also with injected magnetosheath particles (not indicated). In the equatorward region B the wave intensity is much lower. Upgoing ions are shown by solid arrows. Since there often is a high-latitude poleward $E \times B$ convection field [Burch et al., 1982], these ions can drift from region B into region A. A poleward moving satellite may observe upflowing low-energy ions at point 1 in Figure 1. Waves and convection drift can be detected at point 2 and may be mapped down to estimate ion heating and drift at lower altitudes. The heated ions can be observed at point 3. In the following we discuss two events where DE 1 crossed the cusp/cleft in an orbit similar to the one sketched in Figure 1.

The DE 1 satellite was launched in September 1981 into an elliptical polar orbit with a 4.7-$R_E$ geocentric distance apogee. The satellite has plasma instruments including two ion mass spectrometers [Sleelley et al., 1981; Chappell et al., 1981], a wave experiment [Shawhan et al., 1981], and a magnetometer [Farthing et al., 1981]. The ion and plasma wave data presented here were obtained in the spin plane which lies in the orbit plane.

2.1. Event 1, Poleward Moving Satellite

Data obtained on August 10, 1984 when the satellite was crossing the cusp/cleft are shown in Figure 2. The satellite was near noon magnetic local time and moving poleward at about 4 $R_E$ geocentric distance. The top panel in Figure 2 shows the low-frequency electric field spectral density. The data are from the 16 sample per second dc electric field measurement obtained from the long-wire antenna and are presented with 1/3-Hz frequency and 3-s time resolution. Since the satellite spin period is 6 s, the measurements represent an average of the electric field both parallel and perpendicular to the ambient magnetic field. However, observations by, for example, the Viking satellite show that broadband waves observed in this region are essentially perpendicular to the ambient magnetic field [André et al., 1988]. Near 0121 and after about 0123:30 UT the broadband wave intensity increased. In particular, the spectral density at the $O^+$ gyrofrequency (0.85 Hz) increased, and this is important for the resonant ion heating we consider. At about 0123:30 UT the satellite entered the cusp/cleft; this time corresponds to the edge between region A and region B in Figure 1.

The second and third panels of Figure 2 show energetic ion composition spectrometer (EICS) energy-time spectrograms for hydrogen and oxygen. During this interval the EICS instrument sampled $H^+$ and $O^+$ at 15 logarithmically spaced energy steps from 10 eV to 17 keV at 24 pitch angles, in 24-s intervals (4 satellite spins). The data obtained dur-
Fig. 2. Data from an event where DE 1 moved poleward into the cusp/cleft. The top panel shows electric field spectral density in units of $V^2 \text{ m}^{-2} \text{ Hz}^{-1}$ (the O\(^+\) gyrofrequency is 0.85 Hz). The second and third panels show count rates of H\(^+\) and O\(^+\) ions with energies ($E$) from $10\,\text{eV}$ to $17\,\text{keV}$. The left and right scales on the grey bar correspond to the observed H\(^+\) and O\(^+\) count rate, respectively, in counts per sample, which is proportional to number flux. The fourth panel indicates the pitch angle. The bottom panel shows count rate (again in counts per sample) of O\(^+\) ions with energies below $65\,\text{eV}$ as a function of spin angle and time, where the solid line indicates the upgoing direction. Note the onset of waves (first panel) and energetic O\(^+\) ions (third panel) at about 0123:30 UT, and the disappearance of low-energy O\(^+\) ions (lowest panel) at the same time.

Intense, relatively local heating of upflowing O\(^+\) ions is indicated by the conic-type distributions with a density of roughly 1 cm\(^{-3}\) that appear in the third panel at about 0123:30 UT. It is the heating of these ions that we consider in detail.

The bottom panel of Figure 2 shows the O\(^+\) counting rate from the retarding ion mass spectrometer (RIMS) instrument. The RIMS instrument measures ions with energies above the spacecraft potential and below about 65 eV. The data are presented in an angle-time spectrogram format. The solid and dotted lines indicate directions of the ambient magnetic field. The data show low-energy O\(^+\) ions flowing up the magnetic field lines before about 0123:30 UT (the equatorward edge of the cusp/cleft). After this time, upflowing cool oxygen ions are not observed. Comparison with the energetic oxygen spectra in the third panel suggests that the cool O\(^+\) ions are energized out of the RIMS energy range after about 0123:30 UT.

Both particle and wave data in Figure 2 indicate a rather sharp equatorward edge of the cusp/cleft at about 0123:30 UT.
Equatorward of this edge, upflowing cool O\(^+\) ions are observed, and on the poleward side, broadband low-frequency waves and energetic O\(^+\) ions are found. In section 3 we use the observed cool O\(^+\) ions and the observed waves as input to a Monte Carlo simulation.

The perpendicular poleward drift \(u_p\) caused by \(E \times B\) convection is also needed as input to the simulation. One way of estimating this drift is to calculate the appropriate moment of O\(^+\) and H\(^+\) distributions. The result indicates a poleward drift of roughly 5 km/s from 0123:30 UT (the equatorward edge) to about 0130 UT, and decreasing after that. However, there is significant scatter in the data. This is not surprising since the convection drift is much smaller than the typical ion velocities and also much smaller than the change in velocity corresponding to the width of the energy channels of the EICS instrument. Also, the bulk of the ions often fall within the lowest-energy channel, which cannot be used reliably for such calculations. Another way to estimate \(u_p\) is to investigate the dispersive pattern of injected H\(^+\) ions. To obtain a relation between the velocity of downgoing H\(^+\) and \(u_p\), we need to know how this drift changes with altitude. Thus we need to introduce a reasonable model of the geometry and the large-scale electric field in the cusp/cleft.

Assuming that the large-scale electric field is caused by equipotentials following the magnetic field lines in a dipole field, we find that \(u_p\) is proportional to \(r^{1.5}\), where \(r\) is the geocentric distance [Burch et al., 1982]. Perpendicular distances in a flux tube in a dipole field also scale as \(r^{1.5}\). Thus the drift in invariant latitude per unit time is independent of altitude. This is one reason why in this paper we consider a simple two-dimensional "box" model of the cusp/cleft region and introduce the coordinate \(x\), orthogonal to \(r\), measured in the poleward direction. We take the width of our two-dimensional model box to be equal to the width of the cusp/cleft at the altitude at which the satellite enters the cusp/cleft. For the rather limited transverse extent of the event (less than 2000 km at the satellite altitude) this two-dimensional box is not a major approximation, and it is used both to estimate the poleward drift and for the simulation and analytic models. In this model box the magnetic field lines are parallel, but the field strength varies as \(r^{-3}\). Thus, in this model the poleward drift \(u = dx/dt\) is independent of altitude. Note the difference between \(u_p\), which is the poleward drift in real space and depends on altitude, and \(u_x\), which is the poleward drift in our model box and does not depend on altitude. Since \(x\) is related to distances in real space at the satellite altitude, \(u_x = u_p\) at this altitude.

The simplified cusp/cleft geometry may now be used to estimate the poleward drift. Figure 3 shows the velocity of downgoing (pitch angles close to 0°) H\(^+\) as a function of distance from the equatorward edge of the cusp/cleft. The satellite velocity perpendicular to the ambient magnetic field is about 2.6 km/s and is directed roughly poleward, so it is straightforward to calculate the distance \(l\) from the satellite to the equatorward edge. Assuming that the H\(^+\) ions were injected at the equatorward edge at a certain altitude and ignoring the small change of the satellite altitude with invariant latitude, the relation between \(u\) (the velocity of downgoing H\(^+\)) and \(u_p\) is given by

\[
u = \frac{h}{l} u_p\]  

where \(h\) is the altitude difference between the injection point and the point where the satellite crossed the equatorward edge. With the assumption that the injection point is 5 RE above the satellite (about 9 RE geocentric distance), it is clear from Figure 3 that a drift of roughly 5 km/s is consistent with the data, at least up to 0130 UT (about 1000 km inside the cusp/cleft). An injection at 9 RE is reasonable [Burch et al., 1982], but injections at higher altitudes are possible and would correspond to lower convection drifts.

Observations of the dc electric field can also be used to obtain the \(E \times B\) drift velocity. The only available electric field component is in the satellite spin plane, roughly in the north-south direction. Thus we can calculate the convection drift only in the direction perpendicular to this plane, roughly in the east-west direction. Note that this is the direction that is not included in our two-dimensional model. Figure 4 shows the available component of the \(E \times B\) drift as a function of satellite position from 0120 to 0135 UT. The eastward drift is increasing as the satellite moves poleward, but is less than 5 km/s most of the time. There is also a peak near 0123:30 UT (the equatorward edge). The drift velocity is one important parameter in our simulation, which is discussed in section 3. Combining the estimates of the drift velocity from the particle and electric field observations, we find that a constant poleward drift of 5 km/s is a reasonable approximation, at least up to 0130 UT.

2.2. Event 2, Equatorward Moving Satellite

In the following we consider another cusp/cleft crossing by DE 1. On March 7, 1984, the satellite was near noon magnetic local time and moving equatorward at about 4.3 RE geocentric distance (Figure 5). We include this event to show that the sudden onset of low-frequency waves and ion heating at the equatorward edge occurs also on this orbit. Furthermore, during this orbit the magnetometer was in its high-sensitivity mode, and three-dimensional magnetic field observations, which may be used to investigate the wave polarization, could be obtained. Note that the spacecraft now is moving equatorward and thus in the opposite direction compared to the case discussed in Figure 2.

The top panel in Figure 5 shows electric field spectral...
density. Just after 1634 UT the wave intensity suddenly decreased, indicating that the satellite left the cusp/cleft region.

The fifth and sixth panels in Figure 5 show EICS spectrograms for hydrogen and oxygen. One of several injection events can be identified by the characteristic signature of precipitating $^3$He ions at 1634 UT. Note that near 1634 UT, in the fifth panel of Figure 5, there is an onset of downflowing hydrogen with energies of a few keV together with significant fluxes of lower-energy hydrogen. The energy of the injected $^3$He disperses to lower energies poleward, i.e., backward in time. Equatorward of the cusp/cleft (after 1634 UT) there are upgoing O$^+$ ion beams in the sixth panel of Figure 5. Poleward of the edge there are O$^+$ conics. No observations of low-energy ions are presented here since the instrument threshold. However, upflowing He$^+$ ions were observed equatorward of the cusp/cleft edge (after 1634 UT), while essentially no cool He$^+$ ions were detected poleward of this edge.

Magnetic field wave power is shown in panels two to four of Figure 5. Panel two shows the magnetic wave component parallel to the ambient magnetic field, while panels three and four give the right and left circularly polarized components. The data before 1631 UT were obtained when the magnetometer was in a mode with lower sensitivity and should be disregarded. The high-sensitivity mode data show intense magnetic field waves inside the cusp/cleft region (before 1634 UT). Here the magnetic waves are nearly perpendicular to the ambient magnetic field and have right- and left-hand components of roughly equal magnitudes. Just after 1634 UT the intensity of the magnetic waves decreases drastically.

Examples of electric and magnetic spectra from this event are shown in Figures 6 and 7. Both spectra show broadband emissions of the type often observed in the cusp/cleft [Andrè et al., 1988]. The first panel below the magnetic spectrum in Figure 7 shows the degree of polarization [Means, 1972], while the second indicates the ellipticity. Some of the electric field spectral density observed at nonzero frequency is probably due to stationary electrostatic structures which are Doppler shifted by the satellite motion, and similarly some magnetic field spectral density may be due to small scale currents. Alfvén waves propagating along the field lines are also likely to occur [Gurnett et al., 1984]. The total ion density is about 5 cm$^{-3}$ with $^3$He$^+$ as the major species, which gives an Alfvén speed of about $1.3 \times 10^6$ m/s. Furthermore, the $|E|/|B|$ ratio at the O$^+$ gyrofrequency (0.63 Hz) is roughly $2 \times 10^6$ m/s. Thus we find that at least part of the observed low-frequency spectral density may be due to Alfvén waves. From Figure 7 it is also clear that there is a significant fraction of left-handed waves near the O$^+$ gyrofrequency, which is necessary for resonant heating to be important.

Both particle and wave data indicate a rather sharp equatorward edge of the cusp/cleft at about 1634 UT. Equatorward of this edge, upgoing O$^+$ ion beams are observed, and on the poleward side, broadband electric and magnetic low-frequency waves and heated O$^+$ conics are found. Thus observations in the cusp/cleft region are consistent with the DE 1 data in Figure 2, and also with Viking observations [Andrè et al., 1988] in the same region.

3. Theory

3.1. Simulation Model

Mean particle calculations have been used to show that broadband low-frequency waves can cause heating of O$^+$ ions in the central plasma sheet (CPS) [Chang et al., 1986]. The basic mechanism is that the left-hand fraction of the waves at and near the local ion gyrofrequency resonates with the gyrating ion, and the heating rate is simply proportional to the corresponding fraction of the spectral density. Using a Monte Carlo simulation [Retterer et al., 1987a] a CPS ion distribution which was in good agreement with the observed ion conic, could be obtained. Recent results show that a more efficient simulation based on Langevin equations can sometimes be used [Crew and Chang, 1988], and two additional conic events have been shown to be well explained via this heating mechanism [Crew et al., 1990]. The Monte Carlo simulation presented here is similar to the calculation used to explain CPS O$^+$ conics [Retterer et al., 1987a]. However, the CPS problem is one-dimensional (ions moving up the field line), while the cusp/cleft problem is two-dimensional (upward moving ions with poleward drift across field lines). As discussed in connection with the poleward drift in event 1, we have included this extra dimension by introducing an orthogonal coordinate $x$ in the poleward direction, thus obtaining a two-dimensional simulation "box."

In our simulations, O$^+$ ions are launched at different altitudes along the equatorward edge of the cusp/cleft. Each
Fig. 5. Data from an event where DE 1 moved equatorward out of the cusp/cleft. The top panel shows the electric field spectral density in units of V² m⁻² Hz⁻¹ (the O⁺ gyrofrequency is 0.63 Hz). The second panel gives the wave magnetic field power in units of Hz(nT)² parallel to the ambient magnetic field for frequencies up to 2 Hz, while the next two panels give the right-hand (RH) and left-hand (LH) perpendicular wave components. Magnetic wave data before 1631 UT should be disregarded. The fifth and sixth panels show count rates of H⁺ and O⁺ ions with energies from 10 eV to 17 keV. The left and right scales on the grey bar correspond to H⁺ and O⁺ ions, respectively. The lowest panel indicates the pitch angle. Note that there are upgoing O⁺ beams after 1634 UT and O⁺ cones and broadband waves before this time.
Fig. 6. Electric field spectrum obtained with data from 1632:00 to 1632:30 UT (inside the cusp/cleft). These data are obtained with booms in the spin plane, roughly in the north-south direction.

Fig. 7. Magnetic field spectrum obtained with data from 1632:00 to 1632:30 UT, and thus simultaneously with the electric field spectrum in Figure 6. One wave field component is directed along the ambient magnetic field (Ra), while the two others are roughly in the east-west (Ph) and north-south (Th) directions. The lower panels give the degree of polarization and the ellipticity.
RIMS data, but we use particles picked randomly from the upgoing part of an O\(^{+}\) distribution with a 0.25-eV temperature and a 10-\(\text{km/s}\) upward drift. The simulation is not very sensitive to the temperature of the initial distribution. However, our final distribution may be more sensitive to initial conditions than simulations corresponding to the CPS [Retterer et al., 1987] since some of our ions have traveled only a rather short distance along the field line. The 10-\(\text{km/s}\) initial upward drift is consistent with EICS data obtained just poleward of the equatorward edge, where heating and adiabatic folding have not changed the parallel velocity much.

We also need to know the fraction of the spectral density that corresponds to left-hand polarized waves. This fraction cannot be determined with the data available for event 1. However, the magnetic wave spectrum from event 2 (Figure 7) indicates that here a significant fraction of the spectral density observed at the O\(^{+}\) gyrofrequency is left-hand polarized, but part of this may be due to spatial structures. In the simulation we take 10\% of the waves to be left-handed for all invariant latitudes. This gives O\(^{+}\) energies consistent with those observed during event 1. Similar assumptions about wave polarization have been used in studies of the CPS [Chang et al., 1986], of the cusp/cleft [André et al., 1988], and of the auroral zone [Crew et al., 1990].

In the simulation presented below, ions were launched at the equatorward edge of the cusp/cleft every 25 m from 15,000 km geocentric distance up to the maximum satellite altitude. We note that many particles that may be launched at the equatorward edge at lower altitudes, or in the cusp/cleft ionosphere, would drift out of the poleward side of the interesting region before reaching the satellite altitude. To predict whether "typical" particles launched at a specific altitude would reach the satellite, an obvious generalization of the heuristic model [Chang et al., 1986], was used. In our simulation a total of about 4\(\times\)10\(^5\) particles were started, and roughly half of these reached the satellite altitude before they drifted out of the poleward side of the simulation region. A test showed that none of 10,000 particles started between 14,500 and 15,000 km reached the satellite altitude within the invariant latitude range of interest.

Figure 8 shows the wave input parameters to the simulation together with the energies of the observed and calculated O\(^{+}\) distributions. The equatorward edge of the cusp/cleft is at about 0123:30 UT (5010 s). The middle panel shows the electric field spectral densities at the O\(^{+}\) gyrofrequency (0.85 Hz) for each satellite spin together with the mean values to guide the eye. Points equatorward of the edge are included for comparison. The lower panel shows the spectral indices used to map the wave intensity to lower altitudes. The upper panel shows the mean energy corresponding to the O\(^{+}\) distributions obtained from the EICS data (solid circles) and from the simulation (open). The theoretically obtained values can be varied somewhat by changing the assumed fraction of the left-hand waves. However, note that both curves first rise and then level off at about 0126 UT (5160 s). No free parameter in the theory has been adjusted to obtain this behavior. The two curves are in good agreement up to about 0130 UT (5400 s), corresponding to a distance of nearly 1000 km along the satellite trajectory. This good agreement between observed O\(^{+}\) energies and the corresponding energies obtained from theory using observed cool ions and observed wave intensities as an input to a simulation is a major result of this report.

After about 0130 UT the moments of the mass spectrometer data indicate a decrease in the poleward drift, although for simplicity a constant drift of 5 \(\text{km/s}\) is used in the simulation. On the other hand, Figure 3 suggests a better fit if the drift is increasing. More significantly, however, the E field data (Figure 4) show an increase of the east-west drift up to 8 \(\text{km/s}\), indicating a turning convection pattern. Thus the problem becomes three-dimensional (particles drifting eastward and not only poleward). Furthermore, particles observed at higher invariant latitudes enter the cusp/cleft at lower altitudes and spend more time in the cusp/cleft waves. Thus mapping of parameters down the field lines become more uncertain, and our assumption of a steady state situation is less valid. It is not surprising that the agreement between theory and observations is best near the equatorward edge of the cusp/cleft.

It is interesting to compare the O\(^{+}\) distribution functions obtained from the EICS instrument and from the simulation. The upper part of Figure 9 shows distributions observed near the equatorward edge (upper left) and inside the cusp/cleft (upper right). The distribution observed near the edge seems to be rather locally heated. This is clear, for example, since this distribution is not much folded toward higher pitch angles. The distribution observed inside the cusp/cleft indicates more nonlocal heating. Here the ions are more affected by adiabatic folding, and they are more "lifted" in energy toward higher parallel velocities. This is what we expect since these particles have spent more time...
in the cusp/cleft waves and have traversed a greater altitude range. The lower part of Figure 9 shows the corresponding distribution functions from the simulation. About 19,000 (left) and 33,000 (right) simulation particles are used to construct these distributions. The particles are sorted into a matrix for plotting purposes, and each particle is taken into account for both positive and negative perpendicular velocities in order to make the distribution symmetric. Detailed comparison of these simulation distributions with the observed distributions is not meaningful since the energy channels of the EICS instrument are rather wide. Thus the ions in both the observed distributions appear to have a broader angular extent, but this may be attributable to the resolution of the instrument, as well as some pitch angle scattering of unidentified origin which we do not attempt to include in any of our theoretical models.

With the neglect of the mirror force term, the kinetic equation for the distribution function $f$ [Retterer et al., 1987a] may be approximated by

$$\frac{v_i}{D_1} \frac{\partial f}{\partial r} + u_z \frac{\partial f}{\partial z} = \frac{1}{v_i} \frac{\partial}{\partial v_{ll}} \left( v_{ll} \frac{\partial f}{\partial v_{ll}} \right)$$  \hspace{1cm} (3)$$

where again $r$ is the geocentric distance and $z$ is the orthogonal distance from the equatorward edge of the cusp/cleft to the poleward observation point. The dependence of $D_1$ on $(r,z)$ has been omitted for brevity. The perpendicular and parallel ion velocities are given by $v_{ll}$ and $v_i$, while $u_z$ is the poleward drift. Using the method of characteristics, we show in the appendix that a Maxwellian ion distribution started at the equatorward edge of the cusp/cleft will evolve according to the formula

$$f(r,z,v_{ll},v_i) = \frac{n}{x^3 v_i^2 v_{ll}^2} \exp \left( \frac{-v_i^2}{v_{ll}^2} - \frac{(v_i - u_z)^3}{v_{ll}^2} \right)$$  \hspace{1cm} (4)$$

where $v_{ll}^2 = v_i^2 + 4u(r,z,v_i)$ and $v_i$, $u_z$, and $n$ are the thermal velocity, the upward drift, and the density of the initial distribution, respectively. The evolution of the distribution is given by the function $w(r,z,v_i)$ with dimension (velocity)$^2$, which amounts to an increased thermal energy perpendicular to the magnetic field. The exact form of this function depends on the details of the ion drift and the disposition of the wave fields, as is described in greater detail in the appendix. Roughly speaking, $w(r,z,v_i)$ increases linearly with the resonant part of the electric field spectral density and with the time spent in the wave fields. As in the simulation, we assume that the geomagnetic field lines are parallel and that the field strength varies as $r^{-3}$. As previously noted, in this simplified geometry the poleward drift $u_z$ does not depend on altitude. To obtain the ion distribution function at a particular point in space for a specific set of input parameters, we need to specify the boundary conditions at the equatorward edge and then calculate $w(r,z,v_i)$. Since we have neglected the mirror force, the shape of the calculated ion distribution in velocity space shape is incorrect to the extent that it bears only the marks of transverse heating; however, the energy input to $f$ is approximately correct. Therefore, it is useful to consider the mean ion energy $E$ of this distribution. A detailed discussion of the analytic model is presented in the appendix, and below we present some numerical results. We consider a region extending from the equatorward edge to $x_0 = 1550$ km, corresponding to the first 10 min of observations inside the cusp/cleft during event 1 (Figures 2 and 8). The satellite is assumed to be at a constant geocentric distance $r_0 \equiv 4 R_E$.

In the following we consider the analytic model, using input parameters similar to those used in the simulation. These parameters are then varied in order to study the effect on the O$^+$ mean energy $E$. We first consider a "standard" reference model where the initial O$^+$ distribution has a temperature of 0.25 eV and an upward drift $u_z$ of 10 km/s. At the satellite altitude, the spectral density of the left-handed

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**Figure 9.** Distribution functions of O$^+$ ions observed by the EICS mass spectrometer (upper panels) and obtained by a Monte Carlo simulation (lower panels). There are two contours of phase space density per decade, and the innermost (highest) contour corresponds to $2 \times 10^6$ s$^{-1}$ km$^{-3}$ km$^2$. The density of the simulation distributions is taken to be 1 cm$^{-3}$, which is the approximate density of the observed distributions. The left distributions are obtained from 0124:45 to 0126:21 UT, i.e., near the equatorward edge (compare with Figure 8), while the right distributions are from 0128:45 to 0130:31 UT. Note that the equatorward distributions are more spread out in velocity space than in the corresponding simulation distributions. How-ever, the sinuadon .;.,.:t...,;...o show {h ...... ionAoncy

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**3.2. Analytic Model**

We may approach a further understanding of the ion heating in the cusp/cleft by augmenting the numerical modeling effort with a simple analytic model. A reason for developing such a model is that it facilitates experimentation with some of the input parameters used in the simulation model. It also serves as a check on the accuracy of the simulation code. In our analytic model we neglect the mirror force as a means of simplifying the process in order to render it amenable to analysis. One motivation for this simplification comes from consideration of the form of the ion distributions obtained both from observations and from the simulation (Figure 9). Both sets of distributions show the effect of the mirror force in what may be termed a secondary manner. That is, the most prominent feature of the simulation distributions is their heating transverse to the magnetic field; the subsequent conversion of this energy into parallel motion is not as marked. The observed distributions appear to have a broader angular extent, but this may be attributable to the resolution of the instrument, as well as some pitch angle scattering of unidentified origin which we do not attempt to include in any of our theoretical models.

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**Fig. 9.** Distribution functions of O$^+$ ions observed by the EICS mass spectrometer (upper panels) and obtained by a Monte Carlo simulation (lower panels). There are two contours of phase space density per decade, and the innermost (highest) contour corresponds to $2 \times 10^6$ s$^{-1}$ km$^{-3}$ km$^2$. The density of the simulation distributions is taken to be 1 cm$^{-3}$, which is the approximate density of the observed distributions. The left distributions are obtained from 0124:45 to 0126:21 UT, i.e., near the equatorward edge (compare with Figure 8), while the right distributions are from 0128:45 to 0130:31 UT. Note that the equatorward distributions are more spread out in velocity space than in the corresponding simulation distributions. However, the simulation distributions show the same tendency as the observations in the sense that the equatorward distribution in velocity space is more locally heated than the distributions from inside the cusp/cleft.
fraction $\eta$ of the waves at the $O^+$ gyrofrequency is taken to be $\eta \times S = 0.1 \times 3 \times 10^{-6}$ V$^2$ m$^{-2}$ Hz$^{-1}$, while the spectral slope $\alpha$ is 1.5 and the poleward drift $u_x$ is 5 km/s. In this standard model, all the parameters are assumed to be constant along the satellite trajectory.

The solid line in Figure 10a shows the mean ion energy obtained from the standard model as a function of distance from the equatorward edge (compare with the upper panel of Figure 8). Since the turbulence is constant along the satellite orbit, the ions gain energy at a steady rate, which transforms into an almost uniform increase in $E$ with $x$. The departures from linearity at larger $x$ are entirely due to the fact that the ions gathered there have been heated partly at lower altitudes where the strength of the turbulence at the local gyrofrequency is lower. This effect increases with $\alpha$ (see Figure 10a), but the spread is not great. The result that $E$ depends only weakly on $\alpha$ validates our use of 1-min averages of $\alpha$ in the Monte Carlo simulation and reduces any concern about the use of a spectral model in obtaining these results. The upward drift can be varied in a similar way; see Figure 10b. This figure shows the result of the standard model, together with results from similar models with other drift velocities that are a factor of 2 higher or lower.

A higher upward drift velocity of course gives a higher initial energy, but lower energies are then obtained for larger $x$ since the ions spend less time in the region just below the satellite altitude where ion heating is most intense. However, varying the initial upward drift does not have a great effect on the $O^+$ mean energies. Similarly, changes of the initial temperature up to some tens of electron volts are not very important for the mean $O^+$ energy. A higher initial temperature gives the same increase of $E$ for all $x$. No figure is given for this case since it is obvious that at large $x$ the relative increase of $E$ due to a higher initial thermal velocity can be neglected.

Variations of the poleward drift $u_x$ may have a more significant influence on the mean ion energy $E$. Figure 11a shows the result of the standard model and results from similar models where $u_x$ has been changed by a factor of 2.

This causes a change of nearly a factor of 2 of $E$, where the lower drift velocity corresponds to longer ion residence time in the cusp/cleft and thus to higher mean energies. Again, the heating is not strictly proportional to the time spent in the region with waves since the heating rate depends on altitude. A change of the spectral density $S$ may of course also influence the mean ion energy. Figure 11b shows the result of the standard model and also indicates the expected result.
that the mean ion energy is proportional to $S$. Variations of the left-handed fraction of the waves, $\eta$, of course give similar results.

The energy $E$ increases much faster with $x$ near the edge ($x = 0$) in the simulation than in the analytic model. This difference is readily explained when we note the peak in the observed spectral density close to the edge (Figure 8). In the simulation this peak causes high heating rates in a rather small region in space. However, such a localized peak cannot easily be included in an analytic model. A very rough approximation of a spectral density that has a peak near the edge and decreases in the poleward direction, can be obtained by considering a wave intensity that decreases linearly with $x$. Results from such models, where the spectral density at the equatorward edge is the same as in the standard model, are shown in Figure 12a. The mathematical details are given in the appendix. The major change with respect to the standard model is that the mean ion energy as a function of $x$ now clearly appears to saturate, which is in better agreement with observations and the simulation (Figure 8). The ions gathered at large $x$ gain less energy in this model because the strength of the turbulence decreases as these ions reach the highest altitudes where they would have experienced the greatest heating. A similar effect causes the more abrupt saturation in the simulation.

The observed total $E \times B$ drift seems to increase in the poleward direction (Figures 3 and 4). Although the observations indicate that a significant part of this drift is eastward rather than poleward, it is worth considering an analytic model where the (poleward) drift increases with $x$. Results from such models, where the poleward drift at the equatorward edge is the same as in the standard model, are shown in Figure 12b. Details of the analytic model are given in the appendix. A larger increase of $u_x$ gives lower mean ion energies due to the shorter residence time of the ions in the region of low-frequency waves. However, modest changes of $u_x$ with $x$ have only a minor influence on the mean ion energy.

In summary we find that modest changes of the upward drift and temperature of the initial ion distribution, and of the spectral slope, have only a minor influence on the mean ion energy. However, variations of the wave intensity and of the $E \times B$ drift are more important for this energy. We also find that it is necessary to consider variations of the wave intensity with invariant latitude to understand the development of the mean ion energy.

4. Discussion and Conclusions

Above we have shown that broadband low-frequency waves can cause significant ion heating in the cusp/cleft. A statistical study of the upflowing cool (a few electron volts) ions, the waves, and the heated (a few hundred electron volts) ions is beyond the scope of this paper. However, preliminary investigations of data from other DE 1 and Viking cusp/cleft crossings indicate that this kind of heating is rather common. One important remaining question is the origin of the waves causing this heating. Some of the spectral density observed at nonzero frequencies is probably due to stationary turbulence and low-frequency waves with short wavelengths which are Doppler shifted by the satellite motion. Shear in the parallel (injected particles) and perpendicular ($E \times B$ drift) directions may locally generate turbulence [D'Angelo, 1977; Gomulkiewicz et al., 1985; 1988; Pritchett, 1987; Lakhina, 1987]. Alfvén waves propagating along the field lines are also likely to occur. The basic mechanism is that a disturbance imposed on a geomagnetic field line at high altitude can propagate along the field line as an Alfvén wave [e.g. Lysak and Dum, 1983; Burnett et al., 1984]. Many Alfvén waves have long wavelengths and are not much affected by Doppler shifts. The electric and magnetic fields observed during our event 2 show that the $|E|/|B|$ ratio is consistent with Alfvén waves, and this is true also for a similar Viking event [André et al., 1988]. Thus it seems very likely that there are Alfvén waves at the local ion gyrofrequency in the cusp/cleft region which can cause resonant ion heating. However, further investigations of the low-frequency waves are needed.

Waves at frequencies other than the ion gyrofrequency may also be important for ion heating in the cusp/cleft. Injected magnetosheath $H^+$ ions may generate waves at multiples of the $H^+$ gyrofrequency and these waves may cause ion heating [Roth and Hudson, 1985]. However, such multiple emissions are only sometimes observed and then usually in the region of more dense magnetosheath plasma. The ion heating we discuss is very common and occurs throughout
the cusp/cleft. Non-resonant heating by electric field fluctuations clearly below the ion gyrofrequency has also been suggested to be important [Hultqvist et al., 1988; Lundin et al., 1990]. Furthermore, electrostatic shocks, especially close to the equatorward edge of the cusp/cleft, may cause ion energization [Barok, 1984], but the possible contribution from this energization mechanism is hard to estimate.

A process where ions simultaneously absorb two waves whose frequencies sum to the ion gyrofrequency can also heat ions perpendicular to the geomagnetic field [Temenin and Roth, 1986; Ball, 1989]. This heating mechanism has been considered in detail [Ball and Andre, 1990], using data from the two events discussed above. The conclusion is that heating by double-cyclotron absorption may contribute to relatively local energization of O+ ions, but that the cyclotron resonance heating by waves around the gyrofrequency discussed in the present report probably is more important.

It is interesting to consider how our understanding of resonant ion heating by broadband low-frequency waves in the cusp/cleft region fits into our knowledge of ion dynamics at high latitudes on both microscales and macroscales. In this report we consider transverse resonant O+ ion heating at altitudes of a few Earth radii in the cusp/cleft region. There are episodic reports of locally heated H+ ions in this region [Peterson, 1985]. These H+ ions may also be heated by the same resonant mechanism, but inside the cusp/cleft it is not possible to distinguish injected/reflected magnetosheath protons from locally heated H+ ions of comparable energies. It is reasonable to expect that the resonance heating mechanism considered here is important also at lower altitudes. The low-frequency waves are known to propagate to ionospheric altitudes [e.g., Temerin and Parady, 1980]. The ion gyrofrequency increases with decreasing altitude, and the broadband spectral density usually decreases with increasing frequency. Thus the spectral density at the local ion gyrofrequency, and hence the ion heating rate, usually decreases with decreasing altitude. Ions heated at a few thousand kilometers may therefore be expected to attain lower energies than those heated at a few Earth radii. Observations in the cusp/cleft of broadband low-frequency waves and O+ ions with energies of about 10 eV discussed by Moore et al. [1986] are consistent with this scenario. From the above discussion one might expect the O+ heating rate to simply increase with altitude (decreasing gyrofrequency). Ions observed at higher altitudes in the magnetotail, however, are not noticeably more energetic than those at a few Earth radii [e.g., Sharp et al., 1981]. However, this is easily understood if the Alfven wave spectrum has a peak at some small but nonzero frequency. Maximum heating then occurs where this peak matches the local O+ gyrofrequency. Indeed, observations with good frequency resolution made by the Viking satellite in the cusp/cleft [Marklund et al., 1990] and in the auroral zone [Lundin et al., 1990], and by the Intercomos-Bulgaria 1300 spacecraft in the auroral zone [Chmery et al., 1988], indicate such a spectral peak between 0.1 and 1 Hz. If the phase velocity of the waves is approximately equal to the Alfven velocity, Doppler shifts in the spectra obtained by a satellite are essentially always small. Since the O+ gyrofrequency at a few Earth radii is in the range 0.1 to 1 Hz, the observations presented in this report may be roughly from the region of maximum O+ ion heating in the cusp/cleft. The maximum ion heating rate of course varies with wave amplitude and thus with geomagnetic activity, but the altitude dependence of the heating rate may still be the same.

Ion outflows that originate in the cusp/cleft region drift poleward into the polar cap. At low energies (less than about 10 eV) the flow has been called the "cleft ion fountain" [Lockwood et al., 1985; Lockwood et al., 1985b; Caudet et al., 1988]. The ions we consider in the present report drift poleward into the cusp/cleft at altitudes of a few Earth radii, are heated to energies of the order of 100 eV, and then drift further poleward into the polar cap. These ions may constitute the source of the magnetotail ion streams reported by Sharp et al. [1981], and of polar cap ion outflows [e.g., You et al., 1985; Chen et al., 1990]. Polar cap outflows of ions with different energies have been given different names because they have been observed by particle detectors covering different energies, but as noted above, all these ions may well have been heated by the same mechanism. The large-scale upward flow of ions from the cusp/cleft region probably is a source of free energy for microphysical processes at higher altitudes. When ions are heated at different altitudes in the cusp/cleft and drift poleward into the polar cap, they may mix with the low-energy (roughly 1 eV) upflowing polar wind [e.g., Gurgiolo and Burch, 1982]. This mixture of hot and cool ion populations may be highly unstable to wave generation [Barakat and Schunk, 1989], and these waves may subsequently modify the particle distribution functions.

In this report we use cool O+ distributions observed when they are drifting poleward into the cusp/cleft at altitudes of a few Earth radii, together with observed wave intensities, as an input to a Monte Carlo simulation. The theoretically obtained hot O+ distributions are in good agreement with the corresponding observed distributions. The simulation results also agree well with an analytic model of ion heating in the cusp/cleft. Although there may be some contribution from other heating mechanisms, our results strongly suggest that a significant part of the ion heating in the cusp/cleft is caused by resonant interaction at the local ion gyrofrequency with broadband low-frequency waves. The upflowing ions heated in this way may contribute significantly to the magnetospheric ion population.

**APPENDIX: ANALYTIC MODEL OF ION HEATING IN THE CUSP/CLEFT**

Here we discuss some details of the analytic model introduced in section 3.2. The purpose is to obtain the function \( w(r, z, \psi) \) for three specific models. Equation (4) of the main text may then be used to obtain the mean ion energy at any point along the satellite trajectory.

The model kinetic equation (3) may be directly solved by the method of characteristics. The basic idea here is to transform to new variables \((w, \psi)\) which satisfy the equations

\[
\frac{\partial w}{\partial \tau} + u_x \frac{\partial w}{\partial x} = 1 \quad (A1)
\]

\[
\frac{\partial \psi}{\partial \tau} + u_x \frac{\partial \psi}{\partial x} = 0 \quad (A2)
\]

where we have suppressed dependencies on \((r, z)\). We note also that we shall suppress all parametric dependencies as well; this includes that of \((w, \psi)\) on \(\psi\). Introducing \(F(s, \psi, \psi_x, \psi_{xx}) = f(r(s, \psi), \psi_x, \psi_{xx}, \psi_{xxx})\) and using the chain rule, we see immediately that the point of the equations above is to convert the left-hand side of equation (3)
into $\partial F/\partial w$ and render the variable $s$ an ignorable coordinate. The equation for $f$ is thus converted to an ordinary diffusion equation for $F$ in $w$ (which could be regarded as a heating “time”) and the cylindrical variable $v_1$:

$$\frac{\partial F}{\partial w} = \frac{1}{v_1} \frac{\partial}{\partial v_1} \left( \frac{\partial F}{\partial v_1} \right) \tag{A3}$$

Here the diffusion coefficient has been scaled away in the change of variables. This equation is readily solved once the initial conditions are appropriately specified. In our problem it is convenient to fix $s$ and $w$ at the edge of the cusp/cleft by $s = r$ and $w = 0$, respectively. Furthermore, we assume that the boundary condition (the “input” ion distribution at the equatorward edge) is an altitude independent Maxwellian:

$$F(s = r, w = 0, v_1, v_\perp) = \frac{n}{\pi^{3/2} v_\perp^2} \exp \left( - \frac{v_\perp^2}{2} - \frac{(v_\parallel - v_0)^2}{2v_0^2} \right) \tag{A4}$$

The equations (A3) and (A4) then determine the distribution completely; the solution appears as equation (4) of the main text.

We note that this treatment can easily be extended to a case where the boundary conditions vary with altitude. Equations (A1) and (A2) describe a drift path from the boundary where the distribution is presumed known, to the position $(r, x)$ where the distribution is desired. Thus to obtain the distribution, we first determine on which characteristic the point $(r, x)$ lies, and then trace this back to the point where the boundary conditions apply. Thus the inclusion of dependencies of $n$, $u_0$, and $v_1$ on $s$ are all trivial generalizations of equation (A4). One could further incorporate a more general shape of the turbulent boundary in the framework of this analysis. We have not done so in the present study in the interest of simplicity. We do point out, however, that such a generalization could easily account for the diminishing heating at later times in Figure 8.

In the models we consider, the poleward drift $u_\parallel$ and the wave intensity (and thus $D_\parallel$) may depend on the spatial coordinate $x$. With considerable generality, we introduce functions $\varepsilon$ and $\Delta$ such that $u_\parallel = u_0 \varepsilon(x)$ and $D_\perp = D_0 (v_0/ro)^{\alpha}\Delta(x)$. Here $D_0$ and $u_0$ are respectively the diffusion coefficient and the poleward drift at the satellite altitude at the equatorward edge. We can then consider characteristics $r(w)$ and $x(w)$ determined by

$$\frac{dr}{dw} = \frac{v_\parallel}{D_\perp} \tag{A5}$$
$$\frac{dx}{dw} = \frac{u_\parallel}{D_\perp} \tag{A6}$$

which are curves of constant $s$. Two integrations are required to solve (A3). The choice of the Maxwellian boundary condition (A4) makes it possible to perform these integrations analytically. The ratio of the solutions (A5) and (A6) gives us the first quadrature $G(x)$:

$$r - s = \frac{v_\parallel}{u_0} \int_0^x \frac{dx'}{\varepsilon(x')} \equiv \frac{v_\parallel}{u_0} G(x) \tag{A7}$$

and from equation (A5) we finally obtain the function $w(r, x)$ as an integral of the composition of $\Delta$ with the inverse of $G$:

$$w(r, x) = D_0 \frac{v_\parallel}{v_\perp} \int_0^\infty dx' \left( \frac{r'}{ro} \right)^{3\alpha} \Delta \circ G^{-1} \left( \frac{u_0}{v_\parallel} \left( \frac{r'^2}{r_0^2} - s \right) \frac{r'^2}{r_0^2} \right) \tag{A8}$$

Below we discuss how equation (A8) can be solved for three different models.

Model 1. Here we include no dependencies on the spatial coordinate $x$ and thus take $\varepsilon(x) = 1$ and $\Delta(x) = 1$. Trivially $G(x) = x = G^{-1}(x)$, and from equation (A7) we see that

$$s(r, x) = r - \frac{v_\parallel}{u_0} x \tag{A9}$$

The integral (A8) now gives

$$w(r, x) = D_0 \frac{v_\parallel}{v_\perp} \left[ \frac{r^{3\alpha + 1} - (s/r_0)^{3\alpha + 1}}{(3\alpha + 1)r_0^{3\alpha + 1}} \right] \tag{A10}$$

where $v_0 = (D_0 r_0)^{1/3}$. In the “standard” reference model described in the main text we have $v_0 \approx 40.9$ km/s.

Model 2. Here we allow a variation of wave intensity along the trajectory, using $\varepsilon(x) = 1$ and $\Delta(x) = 1 - x/x_\Delta$. Again, $G$ is the identity, and equation (A9) gives $s(r, x)$. Equation (A8) now gives

$$w(r, x) = D_0 \frac{v_\parallel}{v_\perp} \left[ \frac{r^{3\alpha + 1} - (s/r_0)^{3\alpha + 1}}{(3\alpha + 1)r_0^{3\alpha + 1}} \left( 1 + \frac{u_0}{v_\parallel} \frac{s}{v_\parallel x} \right) \right] \tag{A11}$$

Model 3. Here we allow a variation of the drift velocity along the trajectory and take $\varepsilon(x) = 1 + x/x_s$ and $\Delta(x) = 1$. This results in logarithmic trajectories:

$$s(r, x) = r - \frac{v_\parallel}{u_0} x \log(1 + x/x_s) \tag{A12}$$

but, owing to the form of the diffusion coefficient, we obtain the same explicit dependence of $w$ on $r$ and $x$ as in model 1, equation (A10).

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