HEATING OF ION CONICS IN THE CUSP/CLEFT

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ABSTRACT

Ion conic distributions are often observed in the cusp/cleft region of the dayside magnetosphere. We show that these ions can be heated by resonant interaction with broadband low-frequency (near the ion gyrofrequency) waves. Data from one cusp/cleft crossing of the polar orbiting DE-1 satellite is studied in detail. Observed cool O^+ distributions and observed wave intensities are used as input to a Monte Carlo simulation. The theoretically obtained hot O^+ distributions are in good agreement with the corresponding observed distributions. This resonant heating by broadband low-frequency waves is important for the outflow of ionospheric ions into the magnetosphere.

I. INTRODUCTION

It is well known that ions in the ionosphere and magnetosphere can be heated perpendicularly to the ambient magnetic 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 km and by satellites up to many thousand km [1]. It is now established that ions of ionospheric origin can be heated and contribute significantly to the magnetospheric plasma [2].

Ion conics are often observed in space plasmas but the details of the heating mechanism(s) are not known. For example, most suggested mechanisms include interaction with waves, but acceleration by double layers may also be possible [1]. 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. In the present report we show that broadband low-frequency (near the ion gyrofrequency) waves can cause significant ion heating in the cusp/cleft region.

The cusp/cleft is a region of the dayside high latitude magnetosphere, extending further than 09.00 to 15.00 magnetic local time (MLT) and with a latitudinal width of a few degrees. 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 [3]. 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. Although the cusp/cleft is a well known region, the boundaries between the cusp, cleft, and other sub-regions are still under investigation [4–6].

The cusp/cleft region is known to be an important source of upwelling O^+ ions [7] and these ions give a significant contribution to the magnetospheric plasma [2]. Many mechanisms may in principle heat the O^+ ions [8]. However, there is strong evidence that broadband low-frequency waves cause much of the energization. Results from the Viking satellite obtained at an altitude of about 3 R_E (geocentric) 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 [9]. 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 [10] shows that observed electric field waves can produce a locally heated ion distribution (90 degree conic) observed close to the equatorward edge of the cusp/cleft [9]. 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**×**B** convection experience a sudden onset of broadband waves. Similar events have been observed at higher altitudes by DE-1 [11]. Here mass spectrometer data is 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 one DE-1 event in detail. We extend the previous studies by using a Monte Carlo simulation to estimate O^+ ion heating not only near the equatorward edge but also inside the cusp/cleft. The result is that broadband low-frequency waves can cause a significant part of the ion heating observed in the cusp/cleft.

II. ION HEATING IN THE CUSP/CLEFT

A sketch showing a satellite moving poleward into the cusp/cleft region is shown in Fig. 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 poleward high latitude **E**×**B** convection field [12] these ions can drift from region B into A. A poleward moving satellite may observe upflowing low energy ions at point 1 in Fig. 1. Waves and convection drift can be detected at 2 and may be mapped down to estimate ion heating and drift at lower altitudes. The heated ions can be observed at 3. In the following we discuss an event where DE-1 crossed the cusp/cleft in an orbit similar to the one sketched in Fig. 1.

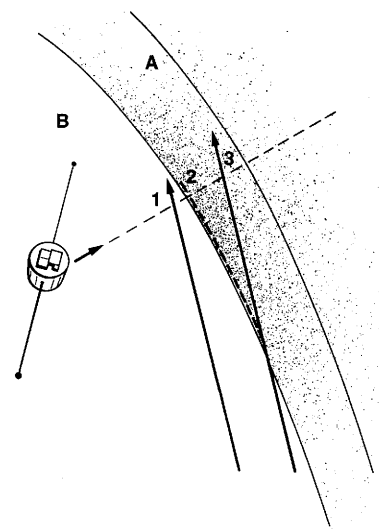

Figure 1. Sketch showing upgoing ions (solid arrows) moving into the cusp/cleft region (A) from the equatorward region (B) due to **E**×**B** convection. The shading in region A indicates low-frequency waves which can heat the ions.

III. OBSERVATIONS

The DE-1 satellite was launched in September 1981 into a 4.7 R_E (geocentric) by 400 km polar orbit. The satellite has plasma instruments including two ion mass spectrometers [13, 14] and a wave experiment [15]. The ion and plasma wave data presented here were obtained in the spin plane which lies in the orbit plane. The basic measurement interval of 6 seconds is set by the spacecraft spin period.

Data obtained on August 10, 1984 when the satellite was crossing the cusp/cleft is shown in Fig. 2. The satellite was near noon magnetic local time and moving poleward at an altitude of about 4 R_E. The top panel in Fig. 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 second time resolution. Since the satellite spin period is 6 seconds, the measurements represent an average of the electric field both parallel and perpendicular to the ambient magnetic field. Near 01:21 and after about 01:24 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 01:24 UT the satellite entered the cusp/cleft and this time corresponds to the edge between region A and B in Fig. 1.

The second and third panels 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 seconds (4 satellite spins). The data obtained during each instrument cycle have been sorted into energy and pitch angle for presentation resulting in the apparent 24 second spin period shown in the pitch angle versus time trace in the fourth panel. Again it is evident that the satellite crossed the equatorward edge of the cusp/cleft at about 01:24 UT. Poleward of the edge the characteristic hydrogen ''butterfly'' pattern caused by the poleward **E**×**B** drift can be seen [12]. No electron data is available for this orbit, but ion injections are usually closely related to injections of electrons [16].

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 01:24 UT. It is the heating of these O^+ ions we consider in detail.

The bottom panel shows the O^+ counting rate from the Retarding Ion Mass Spectrometer (RIMS) instrument. The RIMS instrument measures ions with energies above the spacecraft potential (roughly 1 eV) and below about 50 eV. The RIMS 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 01:24 UT (the equatorward edge of the cusp/cleft). After this time,

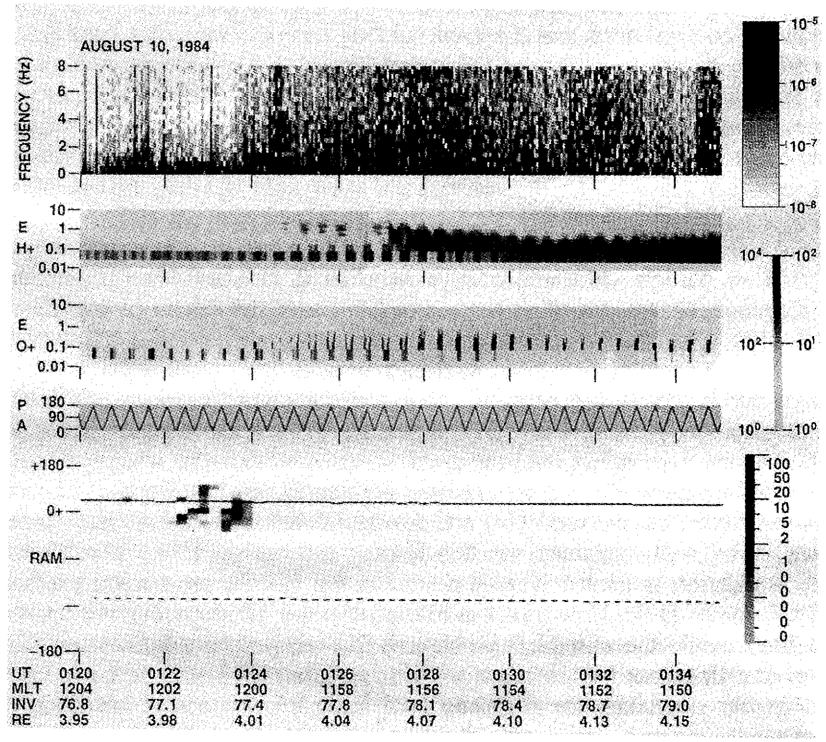

Figure 2. Data from an event where DE-1 moved poleward into the cusp/cleft. The top panel shows electric field spectral density in units of $V^2/(m^2Hz)$ (the O^+ gyrofrequency is 0.85 Hz). The second and third panels show count rates of H^+ and O^+ ions with energies from 10 eV to 17 keV. The left and right scales on the greybar corresponds to H^+ and O^+ ions, respectively. The fourth panel indicates the pitch-angle. The bottom panel shows count rate of O^+ ions with energies below 50 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 heated O^+ ions (third panel) at about 01:24 UT, and the disappearance of low energy O^+ ions (lowest panel) at the same time.

upflowing cool oxygen ions are not observed. Comparision 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 01:24 UT.

Both particle and wave data in Fig. 2 indicate a rather sharp equatorward edge of the cusp/cleft at about 01:24 UT. Equatorward of this edge upflowing cool O^+ ions are observed, and on the poleward side broadband low frequency waves and heated O^+ ions are found. In the following we show that the observed waves can heat the observed cool ions to the energies of the observed hot ions. This conclusion is consistent with a previous study of the same event [11] and with an investigation of a similar Viking data [9].

IV. THEORY

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) [10]. The basic mechanism is that the left-hand fraction of the waves at the local ion gyrofrequency is in resonance with the gyrating ion, and the heating rate is simply proportional to the corresponding fraction of the spectral density. Using a Monte Carlo simulation [17] a CPS ion distribution could be obtained, which was in good agreement with the observed ions. Recent results show that a more efficient simulation based on Langevin equations sometimes can be used [18] and two additional conic events have been shown to be well explained via this heating mechanism [19]. The Monte Carlo simulation presented here is similar to the calculation used to explain CPS O^+ conics [17]. However, the CPS problem is 1D (ions moving up the field line), while the cusp/cleft problem is 2D (upward moving ions with a poleward drift across field lines).

In our simulation the magnetic field lines are assumed to be straight, but the field strength varies as r^{-3} (where r is the geocentric distance in a dipole field). Particles are launched at different altitudes along the equatorward edge of the cusp/cleft. Each particle is then followed in small time steps up to the satellite altitude. For each time step the change in perpendicular velocity due to interaction with the waves, the adiabatic folding, the poleward drift due to **E**×**B** convection and the upward motion due to the parallel velocity is calculated. In the simulation of the DE-1 event presented here we concentrate on the time interval 01:24 to 01:34 UT, corresponding to invariant latitudes from 77.4 to 79.0 degrees.

One advantage with the cusp/cleft geometry is that the "input" cool ion distribution can be observed (at point 1 in Fig. 1). The details of the cool ion distribution can not be determined from the RIMS data, but we use particles picked randomly from the upgoing part of a 0.25 eV O^+ distribution with a 10 km/s upward drift taken as a reasonable value. The simulation result 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 [17] since some of our ions have traveled only a rather short distance along the field line. The 10 km/s initial 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. In the simulation presented here particles were launched every 50 m from the

maximum of the satellite altitude down to 15000 km geocentric altitude. Basically all particles launched at lower altitudes left the simulation region before reaching the satellite altitude.

For each simulation time step the local poleward drift and the spectral density at the local ion gyrofrequency are needed. The simulation region has been divided into 100 bins, each bin corresponding to one satellite spin. For each time step the parameters observed at the satellite in the appropriate bin can be mapped down to the altitude of the ion (along the dashed line labeled 2 in Fig. 1). No reliable E-field data is available in the east-west direction, which would be needed to calculate the poleward drift. The drift is instead estimated by taking moments of the EICS O^+ and H^+ distributions. The poleward drift can also be estimated by investigating the dispersive pattern of injected H^+ (high energy particles arriving near the equatorward edge, slower particles more poleward). The moment calculations give a poleward drift of roughly 5 km/s up to about 01:30 UT and decreasing after that. An investigation of the injected H^+ gives the same result when the injection point is assumed to be at 9 R_E. We take the drift to be 5 km/s at the satellite altitude for all invariant latitudes. The variation of the drift with altitude is assumed to be proportional to $r^{1.5}$. This corresponds to a large scale electric field caused by equipotentials following the magnetic field lines in a dipole field. To determine the other parameter that is mapped down the field lines, the wave spectral density, we assume that the shape of the spectrum is independent of altitude. Over the relevant range of frequencies, the observed field can be reasonably well approximated by a power law with some spectral index α [10], and these approximate spectra are used in the simulation. We also need to know the fraction of the spectral density that corresponds to left hand polarized waves (rather than waves polarized in the opposite sense or Doppler shift of stationary inhomogeneities). This fraction can not be determined with the data available for this event. We take 10% of the waves to be left-handed for all invariant latitudes. This gives roughly the right O^+ energies for this event and is consistent with other studies in the CPS [10], the cusp/cleft [9] and in the auroral zone [19].

Fig. 3 shows the 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 01:24 UT (5040 s). The mid-panel shows the electric field spectral densities for each satellite spin together with mean values included 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 energies can be varied somewhat by changing the assumed fraction of left-hand waves. However, note that both curves first rise and then level off at about 01:26 UT (5160 s). There is no free parameter in the theory that has been adjusted to

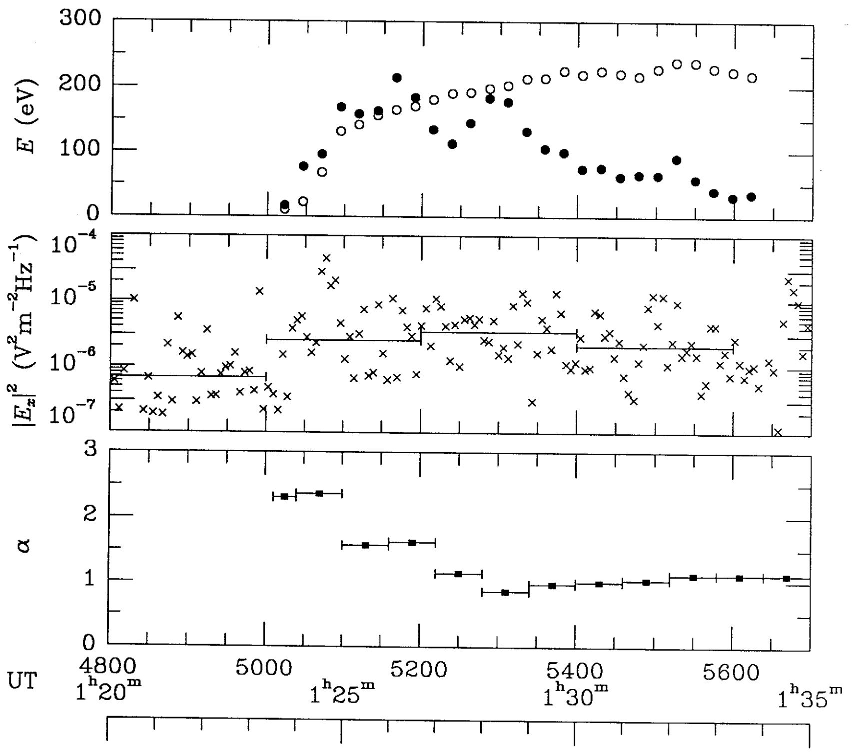

Figure 3. The upper panel shows cusp/cleft O^+ mean energies (E) obtained by DE-1 (solid circles) and from a simulation (open) as a function of time (UT on August 10, 1984 given both as seconds after midnight and as hours and minutes). The mid-panel shows the spectral density $|E_x|^2$ at the O^+ gyrofrequency. Mean values are also included in this panel. The lowest panel shows the spectral index α. The satellite moves poleward into the cusp/cleft at about 5040 s (01:24 UT) where the wave intensity increases and ion heating starts.

obtain this behavior. The two curves are in reasonable agreement up to about 01:30 UT (5400 s). After this time the particle data show a decrease in the poleward drift, although for simplicity a constant drift of 5 km/s is used in the simulation. More important, the available E-field data shows an increase of the east-west drift up to 8 km/s, indicating a turning convection pattern. Thus the problem becomes 3D (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 becomes more uncertain and our assumption of a steady state situation is less valid. It is not surprising that agreement between theory and observations is best reasonably close to the equatorward edge of the cusp/cleft. This good agreement between observed O^+ ion 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.

Detailed investigation of the observed ion distribution functions reveal that the equatorward distributions in the cusp/cleft are rather locally heated (only some folding toward high pitch-angles). More poleward distributions seem less locally heated since they are more folded, more spread out in velocity space and more "lifted" in energy toward higher parallel velocities. This is what we expect since these particles have spent longer time in the cusp/cleft waves. Distributions obtained from the simulation show the same tendency. Thus again there is good agreement between observations and our simulation.

V. DISCUSSION

Above we show that broadband low-frequency waves can cause significant ion heating in the cusp/cleft. One important remaining question is the origin of these waves. Shear in the parallel (injected particles) and perpendicular (**E×B** drift) directions may locally generate turbulence [20]. There may also be propagating Alfvén waves [21]. Other studies of ion heating in the cusp/cleft indeed show that the **E/B** ratio is consistent with Alfvén waves [9,11]. However, further investigations of the low-frequency waves are needed.

Waves at frequencies other than the ion gyrofrequency may be important for ion heating in the cusp/cleft. Injected magnetosheath ions may generate waves at multiples of the ion gyrofrequency and these waves may cause ion heating [22]. However, such multiple emissions are only sometimes observed and then in the region of more dense magnetosheath plasma. The ion heating we discuss is very common and also occurs close to the equatorward edge of the cusp/cleft. Non-linear ion heating caused by emissions at roughly half the ion gyrofrequency may also occur [23, 24], but the efficiency is hard to estimate due to its strong dependence on the wavelength. Non-resonant heating by waves clearly below the ion gyrofrequency has also been suggested to be important [25]. Electrostatic shocks, especially close to the equatorward edge of the cusp/cleft, may also contribute to ion energization [26], but again this heating is hard to estimate.

In this report we use cool O^+ distributions observed when they are drifting poleward into the cusp/cleft at high altitudes 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. 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.

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