HEATING OF THERMAL IONS NEAR THE EQUATORWARD BOUNDARY OF THE MID-ALTITUDE POLAR CLEFT

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ABSTRACT. Intense, energetic oxygen ions are frequently observed to be heated near the equatorward boundary of the mid-altitude polar cleft on the Dynamics Explorer -1 satellite. These observations confirm reports from the VIKING satellite. In this paper we present examples of heating of oxygen ions equatorward of the 'central' cusp/cleft region and use simultaneously obtained low-frequency electric and magnetic field observations to quantitatively test resonant and non-resonant heating processes. We find that, within observational and model uncertainties, the heating rates inferred from observed electric field spectra are large enough to produce the observed perpendicular oxygen temperatures in time scales determined by the measured poleward drift rate of thermal oxygen ions. The examples presented provide a good comparison of basic plasma theory and observation.

Introduction

The entry of intense fluxes of shocked solar wind (magnetosheath) plasma into the polar cusp region creates plasma waves and instabilities which heat and help extract significant quantities of plasma from the ionosphere. The wide variety of plasma waves

observed in the cleft and cusp regions, both from the ground and in-situ, indicate that several different plasma processes are involved in heating ionospheric plasma. To understand this aspect of electromagnetic coupling in the mid-altitude cusp/cleft region, it is necessary to both understand how energy is transferred to ionospheric plasma by the different processes and to determine the relative geophysical importance of various microphysical processes.

Recent reports from the VIKING satellite (Andre et al., 1988) have revealed unexpected, intense heating of thermal ions at mid-altitudes near the equatorward edge of the cusp/cleft region, not in the region of the most dense magnetosheath plasma. Andre et al. found that the ion heating region was closely associated with a strong spatial gradient in the low-frequency (i.e. in the range of ion gyrofrequencies) electric field turbulence. The ion heating regions were identified by angular distributions that show peaks not aligned with the local magnetic field. These ion distributions, which are commonly called ion conic distributions, were first described by Sharp et al. (1977). Andre et al. suggested that 1) the observed ions were oxygen and 2) that they were resonantly heated by the simultaneously observed broad-band, low-frequency plasma waves that have a very sharp gradient in intensity equatorward of the cusp/cleft region. The process suggested by Andre et al. is that thermal oxygen equatorward of the cusp/cleft region drifts poleward into the region of intense low-frequency waves and is heated. This process could be geophysically important because it results in a new, high altitude source of magnetospheric energetic O+ ions. The geophysical conditions (geometry) in the cusp also provide an excellent laboratory in which the predictions of a resonant heating mechanism (Chang et al, 1986) and a non-resonant heating mechanism (Temerin and Roth, 1986) can be tested with in-situ data.

In this paper we demonstrate that data obtained by the Dynamics Explorer (DE) -1 satellite qualitatively confirm the model presented by Andre et al. (1988). We then present examples of mid-altitude (r/Re ~4) heating of oxygen ions equatorward of the cusp/cleft region obtained from the DE -1 satellite. We then use simultaneously obtained low-frequency electric and magnetic field observations to quantitatively test the resonant and the non-resonant heating process.

Observations

The DE -1 Satellite was launched in September 1981 into a 4.7 r/Re by 400 km, 90 degree inclination orbit. The satellite has a complement of plasma instruments including two ion mass spectrometers (Shelley et al. 1981, Chappell et al. 1981), a multi-function plasma wave instrument (Shawhan et al., 1981) and a high resolution magnetometer (Farthing et al. 1981). The ion distributions and plasma wave data presented here were obtained in the satellite spin-plane which lies in the orbit-plane. The basic measurement interval of 6 seconds is set by the satellite spin period.

The cusp/cleft region can be identified by its unique signatures in each of the plasma instruments. Peterson (1985) has presented and discussed the unique cusp signature in the Energetic Ion Composition Spectrometer (EICS) data. We have used this characteristic signature to identify intervals when the satellite passes through the cusp/cleft region and have found that intense energetic oxygen conic distributions were frequently observed equatorward of the most intense downward fluxes of energetic H+ and He++ ions as suggested by Andre et al. (1988). Figure 7 in Peterson (1985) presents a typical example.

We also occasionally detected intense H+ and He+ ion conic distributions equatorward of the central cusp/cleft region.

To quantitatively test the resonant heating mechanism suggested by Andre et al. (1988) we have assembled high resolution data from the relevant DE -1 instruments for three cusp crossings in 1984 where oxygen ion conics were also observed. We required that several complete energy-mass-angle ion distributions be acquired between the region of most intense downward flowing H+ ions and the equatorward onset of the observed oxygen ion conics. This requirement led us to consider only cusp passes above r/Re ~3.5; at these altitudes the local oxygen ion gyrofrequency is ~1 Hz.

In addition to data from two ion mass spectrometers, plasma wave data in the frequency range 0 to 8 Hz was obtained from the Fourier transform of the 16 sample per second DC electric field measurements (Shawhan et al., 1981). In one case three dimensional magnetic field spectra over the same frequency range were available. Figures 1 and 2 present an overview of the observed ion mass-energy-angle spectra and electric field data from two of the three events studied in detail. Note that the time scales are not uniform. Universal time is indicated below the third, fourth, and fifth panels. Altitude in units of r/Re, McIlwain L parameter, magnetic local time (MLT) and geomagnetic latitude (MLAT) are indicated only below the fifth panel.

Figure 1 presents data obtained on August 10, 1984 when the spacecraft was crossing the cusp into the polar cap near noon magnetic local time. The top two panels show EICS energy-time spectrograms for hydrogen (top) and oxygen for a 7 minute interval starting near 01:20. The observed count rate, in units of counts per second which is proportional to number flux, is encoded using the gray bar on the right. 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 spin periods). The display illustrates that energy sampling is not contiguous by showing gaps between energy bins. 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 vs.time trace in the third panel. The characteristic hydrogen cusp signature begins in the instrumental cycle starting at ~01:23:30. This butterfly pattern has been discussed at length by Peterson (1985) and Burch et al. (1982). The region of most intense downward flowing hydrogen ions, and therefore downward flowing cusp electrons,(Burch, 1985) was observed after 01:27. On this crossing of the cusp, only one plasma injection region was observed. Typically more than one injection event such as that beginning at 01:23:30 is observed (see, for example, Peterson, 1985).

Intense, relatively local, heating of the oxygen ions is indicated by the conic-type angular distributions that appear in the instrument cycle starting just before 01:24 in the second panel. Because of the way that the data are sampled, it is possible that oxygen heating began during the previous instrumental cycle that included the onset of the cusp/cleft ion signature. The oxygen angular distributions shown do not all peak at the same angle; they peak at smaller angles at lower energies. Klumpar et al. (1985) have noted the frequent occurrence of this type of angular distribution and have called them bi-modal. They pointed out that bi-modal distributions could be produced by both parallel and perpendicular acceleration mechanisms occurring together or in series on the same magnetic field line. Temerin (1986) and Chang et al. (1986) have shown that transverse heating over an extended altitude range also produces bi-modal conic distributions.

The bottom panel shows the observed oxygen ion counting rate from the Retarding Ion Mass Spectrometer (RIMS) instrument for the interval from 01:10 to 1:34. The RIMS
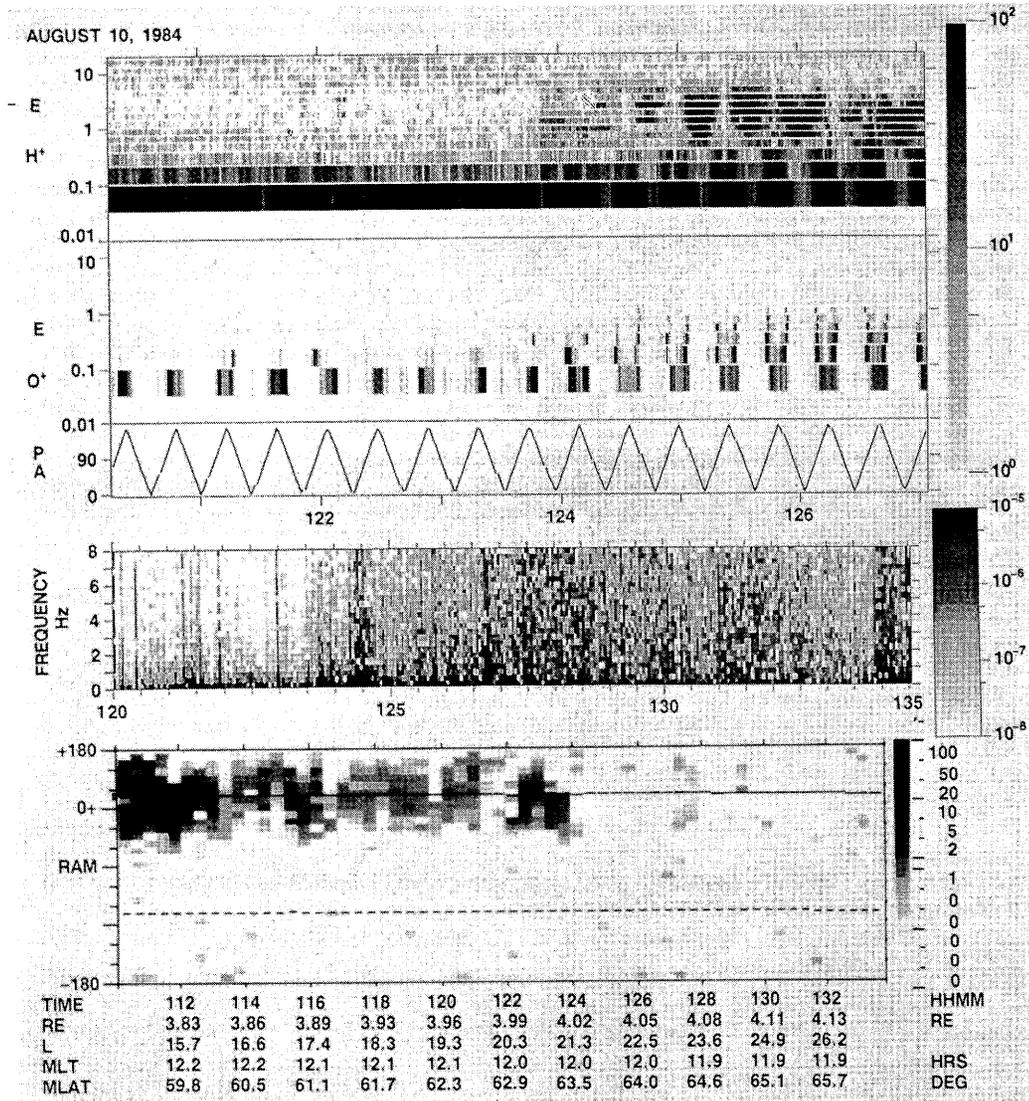
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Figure 1. Ion and plasma wave data obtained from Dynamics Explorer -1 on August 10, 1984. Note that the time scale is different for the bottom two panels.

count rate, which is proportional to the number flux of ions with energies above the spacecraft potential (~1 eV) and below ~50 eV, is encoded using the gray bar shown on the right. The RIMS data are presented in an angle-time spectrogram format. The solid and dotted lines indicate directions of the magnetic field. The RIMS data show a strong flux of thermal oxygen ions flowing up the magnetic field line before ~01:24. Upflowing thermal oxygen ions are not observed after ~01:24. Comparison with the energetic oxygen spectra in the second panel suggests that the thermal oxygen ions are energized out of the RIMS energy range after ~01:24.

The fourth panel in Figure 1 presents the electric field power-spectral density derived from the 16 sample per second DC electric field measurements obtained from the long wire antenna. The power-spectral density in units of $V^2/M^2/Hz$ has been encoded using the gray bar on the right. These measurements were made in the plane of the spacecraft and therefore are an average of the electric field spectrum both parallel and perpendicular to the local magnetic field. The data are presented with 1/3 Hz frequency and 3 second time resolution. Near 01:21 and after ~01:23:30 the wave power is more intense.

Detailed examination of the energetic oxygen ion distributions from 01:23 to 01:25 show that they are characterized by drifts in the spacecraft frame of ~20 km/s upward and ~10 km/s poleward and perpendicular to the local magnetic field in the satellite spin-plane. Since the satellite motion is 3km/sec poleward, the poleward drift of the ions is $10 + 3 = 13$ km/s. Near 01:23 the RIMS oxygen distribution has a density of ~1 cm^{-3} and a temperature on the order of a few eV. Near 01:25 the EICS oxygen distribution has a density of ~1 cm^{-3} and a bulk temperature perpendicular to the local magnetic field of ~150 eV.

The data in Figure 1 are consistent with the model suggested by Andre et al. (1988). Specifically, thermal oxygen is present equatorward of the cusp/cleft and equatorward of a relatively sharp boundary in the low-frequency wave field; thermal oxygen is drifting poleward and is energized perpendicularly to the magnetic field poleward of the low-frequency wave boundary. To quantitatively check this model we proceed as follows: we compare the measured oxygen temperature perpendicular to the magnetic field obtained at a point poleward of the low-frequency wave boundary with the expected temperature inferred from the product of a calculated heating rate and an estimated time for ions to move from the wave boundary to the point where the perpendicular temperature is determined. To estimate this 'exposure' time we note that the distance the satellite travels from the time it crosses the wave boundary at 01:23:30 to 01:25 where we have determined the oxygen perpendicular temperature is ~270 km (90 s x 3 km/s). If the wave boundary is stationary with respect to the earth's magnetic field and perpendicular to the direction of satellite motion, then it takes plasma approximately 20 seconds to drift this distance (20 s ~270 km /(10+3)km/s). If the boundary was oblique to the satellite path or was moving poleward or equatorward the real 'exposure' time could be longer or shorter than 20 seconds. The rate of cusp/cleft movement at radial distances of r/Re ~ 4 is not expected to exceed ~1 km/s, however, even during quite active periods (Eather et al. 1979).

Using the exposure time of 20 seconds inferred from the simplest possible geometry we see that a heating rate of ~7 eV/s ((150-10)eV / 20 s)would be required to energize the thermal plasma observed before 01:23:30 to the 150 eV energy observed at 01:25. We now use the average power-spectral density in the electric field data from 01:24 to 01:25 and either a resonant heating mechanism proposed by Chang et al. (1986) or a

non-resonant heating mechanism proposed by Temerin and Roth (1986) to calculate heating rates.

The observed average power-spectral density from 01:24 to 01:25 in the vicinity of the oxygen gyrofrequency (~0.85 Hz) is ~1 x 10^{-5} $V^2/M^2/Hz$. Using equation 4 from Chang et al. (1986) we obtain a heating rate of 30 eV/s. The product of the estimated heating rate and exposure time is ~4 times the observed oxygen ion heating of ~150 eV which is consistent with the observations, given the expectation that much of the wave power is in modes which do not participate in ion heating. To calculate the non-resonant heating rate using equation 4 from Temerin and Roth (1986) we use the power-spectral density measured at half the oxygen gyrofrequency (~3 x 10^{-5} $V^2/M^2/Hz$), assume a perpendicular wavelength of 100 km, and a bandwidth of 0.5 Hz. The 100 km perpendicular wave length was chosen as a typical cusp/cleft scale size; smaller wavelengths would correspond to higher non-linear ion heating. These assumptions lead to a heating rate of ~0.9 eV/s. The non-resonant heating rate is sensitive to the assumptions made on both the average and peak electric field strength and this leads to greater uncertainties in our estimate. If the electric field power spectral density has been thus undervalued, the non-resonant heating mechanism can account for the observations. We defer a discussion of uncertainties in the above comparisons until we have presented the data from a second example.

Figure 2 displays data acquired on March 7, 1984 in the same format as Figure 1 except that the RIMS ions displayed in the bottom panel are He+ rather than O+. During the interval on March 7, 1984, the flux of O+ ions below ~50eV was below the RIMS instrumental threshold. Note also that on March 7 the satellite direction was from the polar cap region through the cusp/cleft and into the magnetosphere which is opposite to that shown in Figure 1. The cusp/cleft region on this pass was highly disturbed, with multiple injection boundaries detected, consistent with a relatively high level of magnetic activity. (The Kp index was 4- and the hourly average AE index was 409.) One of the several cusp injection events can be identified by the characteristic signature of precipitating hydrogen ions near 16:34. Note that near 16:34, in the top panel of Figure 2, there is an onset of downflowing energetic (~5 keV) hydrogen above a strong flux of low energy hydrogen, that disperses to lower energies (~1 keV) poleward, i.e. backward in time. The time 16:34 also corresponds to a very sharp boundary in the electric field power- spectral density (fourth panel), and the disappearance of low energy upflowing He+ ions. Poleward of 16:34 energetic bi-modal oxygen conics (second panel) are clearly present; equatorward are beams of energetic upflowing oxygen.

Detailed examination of the energetic oxygen distributions obtained poleward of 16:34 at 16:33:45 and equatorward at 16:35 show that they are both characterized by bulk upward velocities of ~40 km/s and densities of ~0.25 cm^{-3}. During the interval from 16:33:30 to 16:35 the drift of the plasma perpendicular to the magnetic field and in the satellite spin-plane fluctuated but had an average poleward velocity of ~20 km/s. The oxygen distribution had a characteristic perpendicular temperature of ~340 eV at 16:33:45. After 16:34 (i.e. equatorward of the region of intense low-frequency waves) the parallel and perpendicular temperatures of the oxygen distribution were approximately equal (~40 eV). The satellite traveled ~45 km from the time of the last complete measurement cycle in the intense low-frequency waves to the boundary at 16:34 (15 s x 3 km/s). If we assume that the wave boundary is stationary with respect to the magnetic field and perpendicular to the orbit-plane, approximately 3 seconds (~45 km / (20-3) km/s) are required for the
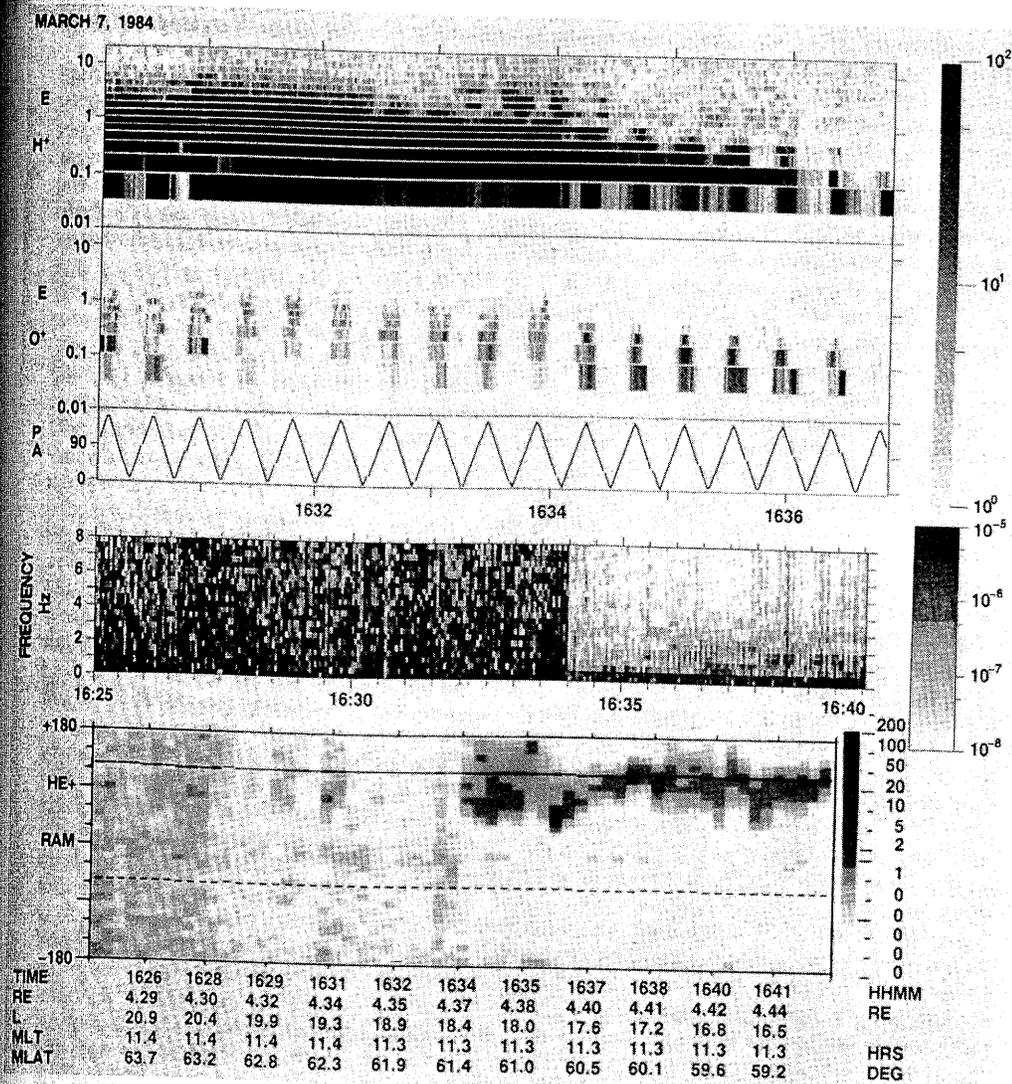
Figure 2. Ion and plasma wave data obtained from Dynamics Explorer -1 on March 7, 1984. Note that the time scale is different for the bottom two panels.

plasma to drift from the boundary to the observation point. Thus a heating rate of 100 eV/s (~(340-40)eV /3 s) would be required to energize the plasma in the 3 second exposure time estimated using the simplest possible geometry.

The resonant oxygen heating rate obtained from equation 4 in Chang et al. (1986) is 60 eV/second using the observed average power-spectral density from 16:33:45 to 16:34:00 of ~2 x 10^{-5} V^2/M^2/Hz near the oxygen gyrofrequency (~0.63 Hz). The product of the estimated exposure time (3 seconds) and heating rate is 180 eV which is slightly less than the 300 eV observed heating, but still consistent with the observations within the uncertainties of the model and the measurements. The non-resonant heating rate calculated using equation 4 from Temerin and Roth (1986) using the average power-spectral density near half the oxygen gyrofrequency of ~5 x 10^{-5} V^2/M^2/Hz, a wavelength of 100 km, and a bandwidth of 0.3 Hz is ~2 eV/s. As noted above the non-resonant heating rate is sensitive to assumptions about the average and peak power power-spectral density.

Because of uncertainties in the absolute values of the parameters used in the heating rate and exposure time calculations above, the oxygen heating rates predicted by both the resonant and non-resonant heating mechanisms are consistent with the observations summarized in Figures 1 and 2. The ion temperatures used and the poleward drift velocities are known to ± 30%. There are slightly larger uncertainties in the absolute value of the measured wave electric field power-spectral densities. However the largest uncertainties in the comparison between the observations and measurement are introduced by 1) the uncertainty in the partition of the observed wave electric field between that parallel and perpendicular to the magnetic field; 2) the assumption that the low-frequency wave boundary is aligned with the local magnetic field and perpendicular to the satellite path; and 3) lack of any information on the polarization of the low-frequency electric field. Only wave energy perpendicular to the local magnetic field is effective in heating ions by either the resonant or non-resonant mechanism. Under the assumption that the wave electric field is isotropic in the plane perpendicular to the magnetic field, the actual electric field power would be three times that inferred from a single electric field antena. This would increase the resonant heating rate 3 times and the non-resonant heating rate 9 times the previously quoted values. The exposure time used in the calculation is made assuming that the low-frequency wave electric field is aligned and stationary with respect to the local magnetic field and perpendicular to the satellite path. If the boundary were inclined to the satellite path generally or locally because of a surface wave in the cusp/cleft/magnetospheric boundary, the calculated exposure time could be several times longer or shorter than the times calculated. Only right-hand polarized waves will not resonantly heat ions and there is no information about the polarization of the electric field available. Chang et al. (1986) and Crew et al. (1988) have found reasonable agreement with observations by assuming that the left-hand polarization near the oxygen ion frequency was on the order of 10 per cent. Calculation of the non-resonant heating rate involves significant additional uncertainties. These are introduced by the assumption of a 100 km perpendicular wavelength and the sensitivity of the mechanism to the electric field strength. The non-linear nature of the mechanism means that local intensification of the power-spectral density would provide significantly more heating than the same power averaged over a longer interval. For these reasons we find that even though the non-resonant heating rates calculated from the time averaged spectra are significantly lower,the mechanism might, under conceivable circumstances contribute a substantial fraction of the heating needed to form the observed

distributions. Unfortunately, the uncertainties in the observations do not allow a quantitative determination of the relative contribution.

On March 7, 1984 there are several additional observations that are consistent with the model proposed by Andre et al. (1988) which we are testing. Specifically the RIMS instrument observed singly charged helium ions after ~16:34, and three dimensional magnetic field spectra are available over the frequency range 0 to 8 Hz. We can use the average electric field spectra to estimate the helium ion heating rates for both the resonant and non-resonant mechanisms. The resonant mechanism gives a helium heating rate of ~70 eV/s; the non-resonant mechanism gives a rate ~0.4 eV/s. If we use three times the average power-spectral density at half the helium gyrofrequency, the non-resonant helium heating rate is ~3 eV/s. We do not have observations of the energetic helium spectra so we can not verify that helium ions acquired enough energy to move them out of the RIMS energy range (0-50 eV) poleward of 16:34; so we can not rule out the possibility that there is no energetic helium poleward of 16:34. On March 7 the magnetometer was in its high sensitivity mode and the three-dimensional, 0-8 Hz magnetic field power spectra obtained from the 16 vector samples per second were above the instrumental noise limit. Examination of these spectra revealed no measurable elliptical or circular polarization perpendicular to the magnetic field at frequencies near the oxygen gyrofrequency. Only the resonant heating mechanism requires left-hand polarized waves. The lack of a measurable polarization is possible if the waves responsible for the energization have a broad wavelength spectrum. Using the electric and magnetic field power-spectral density near 16:34 we calculate an Alfvén velocity of $~3 \times 10^3$ km/s which is consistent with the value estimated using the measured mass density and magnetic field intensity. In addition field aligned currents observed from 16:31 to 16:40 were significantly less than those observed in the region of most intense cusp ion precipitation before 16:31.

Discussion

We have examined the energetic ion composition data for many transits of the mid-altitude cusp/cleft region by the Dynamics Explorer -1 satellite and have found that oxygen ions frequently are heated well equatorward of the region of most intense downward fluxes of magnetosheath plasma. These observations are consistent with those reported by Andre et al. (1988) and confirm the existence of an unexpected mechanism for energizing oxygen at mid-altitudes in the cusp/cleft.

We have used the data summarized in Figures 1 and 2 to quantitatively confirm the model proposed by Andre et al. (1988) to explain this unexpected heavy ion heating region. We have found that the heating rates inferred from resonant (Chang et al. 1986) and non-resonant (Temerin and Roth, 1986) heating mechanisms are large enough to produce the observed perpendicular oxygen temperatures in time scales determined by the poleward drift rate of thermal oxygen ions found well equatorward of the cusp/cleft region. We have also discussed the uncertainties in the measurements and geometry of the the model and the measurements.

The examples presented provide an unusually clean comparison of theory and observation. As noted by several investigators (e.g. Peterson et al., 1988) unambiguous comparisons between space plasma data and theory have proven to be extremely difficult. We discuss below two of the ambiguities in the data reported here that are perhaps inconsistent with the simple model we have tested. First there is a feature in the data for the August 10 event (Figure 1) that can be interpreted as an electrostatic shock which could be

responsible for some of the oxygen heating observed. Secondly we consider the source and nature of the sharp boundary in the low-frequency wave field. We also note that we expect that other heating mechanisms are operative in the mid-altitude cusp/cleft.

The intensification in the low-frequency wave power near 01:24:30 in Figure 1 is associated with a ~10s interval where the DC electric field ramps up to over 20 mV/m and back down. This feature can be interpreted as a perpendicular electric field shock and as such could energize oxygen with energies greater than ~10 eV perpendicular to the magnetic field as discussed by Lennartsson (1980) and Borofsky (1984). Since the oxygen conic ion angular distribution after 01:24 is strongly peaked in angle and not exactly at ninety degrees to the magnetic field, the perpendicular heating must have occurred over a rather limited altitude range below the satellite. However, the source altitudes of oxygen heating regions inferred from detailed examination of individual angular distributions are not consistent with a single source altitude. This fact does not prove that the oxygen ions on August 10, 1984 are not heated as they pass through an electrostatic shock, but suggests that a series of shocks is required to produce the observed angular distributions. The feature near 01:24:30 in Figure 1 is the only one that could be interpreted as a perpendicular electrostatic shock found in the three cusp crossings examined in detail. It is possible to measure the perpendicular oxygen temperature at several times after 01:24 to determine if the observed increase indicated in Figure 1 is consistent with the resonant or non-resonant wave heating rates inferred. The software to perform this comparison is under development. This comparison will help resolve the ambiguity in the interpretation of Figure 1.

The source and nature of the strong gradient in low-frequency electric field found in the cases examined here and the results summarized by Andre et al. (1988) are not well known. Gurnett et al. (1984) have reported correlated low-frequency electric and magnetic noise along cusp, cleft and auroral field lines in the altitude range from 1.1 to 3 r/Re. Gurnett et al. (1984) were unable to determine if the observed low-frequency wave spectra, which are similar to those reported here, were due to static electric fields embedded in the ionosphere or electromagnetic embedded waves propagating from the magnetosphere into the ionosphere. It should also be noted that Temerin and Parady (1980) have reported low-frequency electric and magnetic field spectra similar to those reported here at ionospheric heights from a rocket. Their report suggests the waves could be caused by static electric fields embedded in the ionosphere.

Finally we note that the simple geometry in the cusp/cleft region where cool ions drift into a region of intense waves provides a particularly well defined test of an aspect of basic plasma theory using observations from spacecraft. Crew et al. (1988) have shown that the resonant heating mechanism also explains to a comparable degree of accuracy the bi-modal oxygen distributions reported by Klumpar et al. (1985).

Acknowledgements

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