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1.0 Research Objectives

The overall objective of this research is to investigate the generation and propagation of electromagnetic ion cyclotron (EMIC) waves in the frequency range from 0.2 to 5 Hz (Pc 1 frequency band). Data used in this research were acquired by the AMPTE/CCE, DE-1, and DE-2 satellites. One of the primary questions addressed in this research is the role which EMIC waves have on the transfer of energy from the equatorial magnetosphere to the ionosphere. The primary result from this research is that some fraction of EMIC waves, generated in the equatorial magnetosphere, are Landau damped in the ionosphere and are therefore a heat source for ionospheric electrons. This result as well as other results are summarized below.

2.0 Summary of Scientific Results

2.1 DE-1 / AMPTE CCE Conjunction Study

An investigation of simultaneous Pc 1 wave observations from DE-1 and AMPTE/CCE was begun in the first year of this work. Unfortunately, after considerable effort it was concluded that the DE-1 magnetic field data set was not in a state conducive for this type of analysis. At that time, Dr. Slavin at GSFC, was in the process of preparing the MAG data set. This work was done by the third year of this proposal but by that time I had begun the analysis of EMIC waves using the DE-2 satellite.

2.2 DE-2 Study of Thermal Electron Heating by EMIC Waves

The principal activity during the past six months has involved the analysis of ion cyclotron waves recorded from DE-2 using the magnetic field experiment and electric field experiment. The results of this study have been published in the Geophysical Research Letters (GRL); the paper is included as part of this report. The primary finding of this paper is that ion cyclotron waves were found to heat electrons, as observed in the DE-2 Langmuir probe data, through a Landau damping process.

A third activity under way involves a comprehensive study of ion cyclotron waves recorded at ionospheric altitudes by DE-2. This study will be an extension of the work reported in the GRL paper and will involve a larger sampling of wave events. This paper will focus on investigating the ionosphere as the region where Landau damping of Pc 1 waves occur.

2.3 DE-2 Statistical Study of Pc 1 Waves in the Ionosphere

A statistical study of Pc 1 waves recorded at ionospheric altitudes have never been performed. Ionospheric observations of Pc 1 waves were first obtained only recently using the magnetic field experiment on the MAGSAT satellite [Iyemori and Hayashi, 1988]. These results were confirmed recently using the VEFI and MAG instruments on DE-2 [Erlandson et al., 1993; Iyemori et al., 1994]. To extend the recent DE-2 observations a statistical study of Pc 1 waves at ionospheric altitudes have been performed. This study will complement other statistical studies performed using ground based Pc 1 data and data recorded in the equatorial magnetosphere. Differences between occurrence distributions and properties may then yield information on wave propagation between the equatorial magnetosphere and the ionosphere. In addition, the ionospheric distribution of Pc 1 waves represent the source of magnetospheric waves to the ground.

The statistical study was based on the identification of Pc 1 waves from 0.4 to 6.0 Hz in the electric field experiment (VEFI) using over one year of data (from 81330 to 83049). The Pc 1 waves were identified using an algorithm designed to select spectral peaks in the VEFI data. The selection criteria also included excluding events with electric field spectral densities greater than 10 $(mV/m)^2/Hz$. This effectively excluded intervals at auroral latitudes which are dominated by broadband noise in the electric field. Using this algorithm 536 events were identified. The power, frequency, location, and magnetic field power at the same frequency was stored for post-processing analysis. Some of the results from this study are summarized below.

Figure 1a shows the frequency of the Pc 1 waves as a function of invariant latitude. The frequency of the waves generally decreased with increasing latitude. This was expected since these waves are generated in the equatorial magnetosphere and propagate along field lines to the ionosphere. The Pc 1 wave frequency in the equatorial plane is controlled by the ion cyclotron frequency which decreases with increasing L-value (or invariant latitude).

It is also found that the waves are generally confined to invariant latitudes less than 62-64°. The population of waves in the outer magnetosphere identified by Anderson et al. [1992] between an L of 7 to 9 is not observed. The reason for this is that the observation of Pc 1 waves at ionospheric altitudes use satellites which move quickly across any given L-shells. However, further explanations are currently under consideration.

The distribution of waves as a function of frequency is shown in Figure 1b. It is seen that the waves occurrence maximizes at around 1 Hz as expected for a source at invariant latitudes less than 63-64°.

The latitude distribution using data from both the southern and northern hemisphere is also shown in Figure 2. The top panel shows the number of satellite observations at a given latitude. The middle panel shows the number of waves at a given latitude. The bottom panel shows the normalized occurrence of Pc 1 waves as a function of latitude. The occurrence rate maximizes at invariant latitudes between 54-62°.

A significant number of other properties were also investigated and are being discussed in a manuscript which is in preparation. These results were also discussed at the Spring 1994 American Geophysical Union meeting.

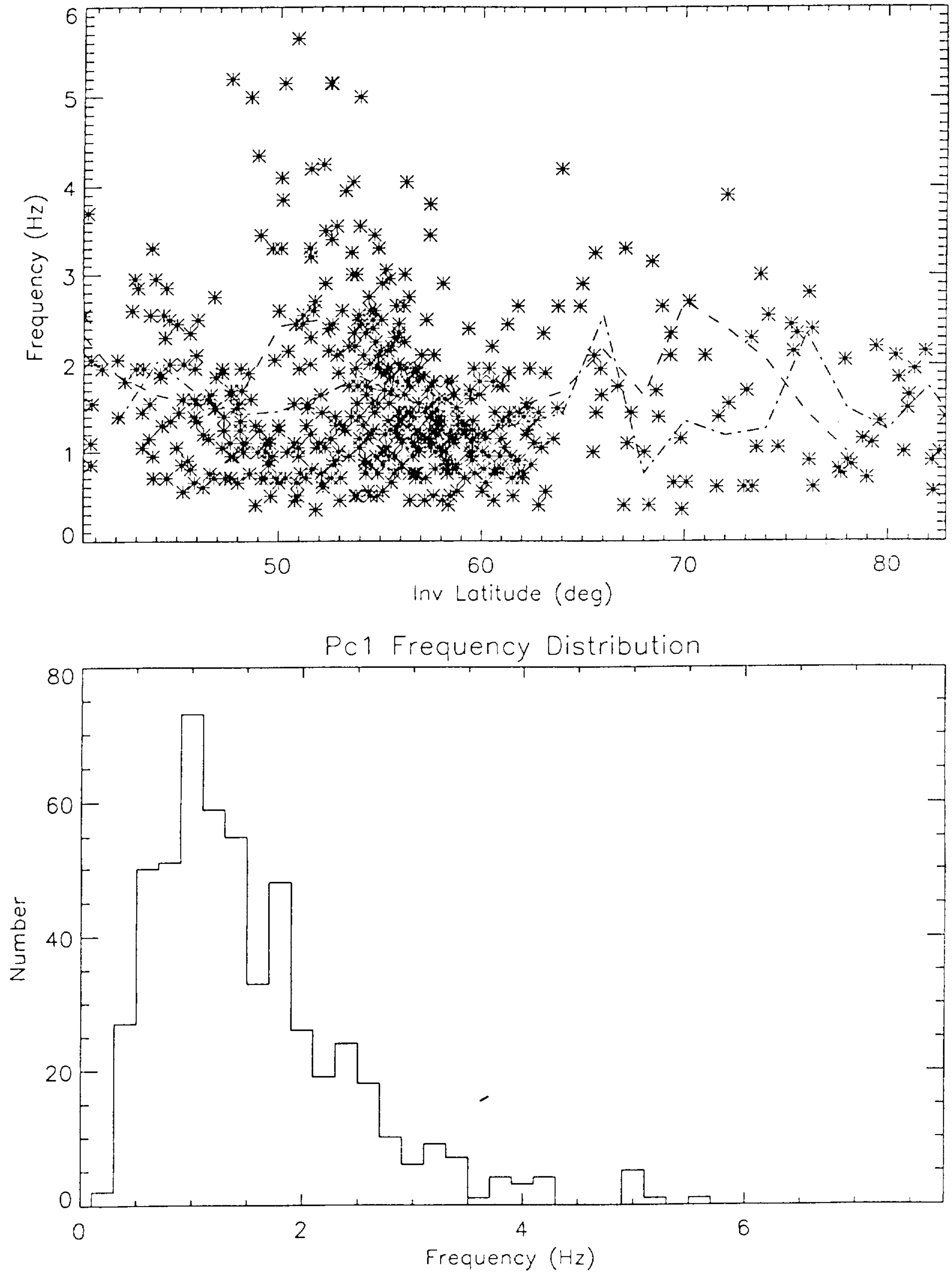

Figure 1. Frequency of Pc 1 waves as a function of invariant latitude.

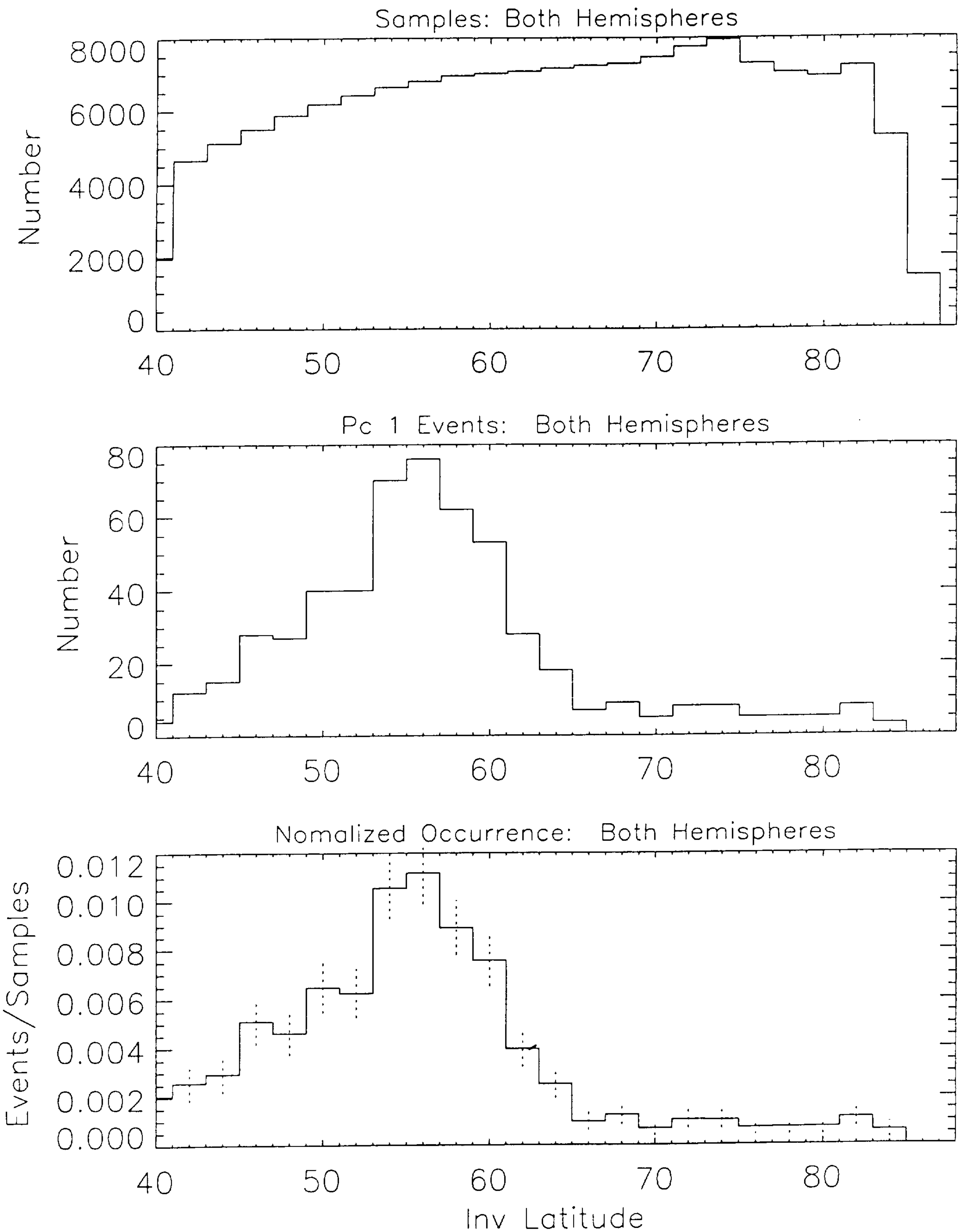

Figure 2. Occurrence rate of Pc 1 waves as a function of invariant latitude. Pc 1 events recorded in both the southern and northern hemisphere are shown in this figure.

3.0 Publication and Presentation List

Erlandson, R. E., T. L. Aggson, W. R. Hoegy, and J. A. Slavin, Simultaneous observations of subauroral electron temperature enhancements and electromagnetic ion cyclotron waves, Geophys. Res. Lett., 20, 1723, 1993.

Erlandson, R. E., A statistical study of Pc 1 waves at observed at ionospheric altitudes, J. Geophys. Res., manuscript in preparation, 1994

Erlandson, R. E., and J. Gary, Heating of ionospheric electrons by Landau damping of Pc 1 waves at ionospheric altitude, J. Geophys. Res., manuscript in preparation, 1994.

Presentations

Erlandson, R. E., B. J. Anderson, and J. A. Slavin, Comparison of Equatorial and High Latitude Pc 1 Wave Observations, EOS, Transactions, American Geophysical Union, 73, 252, 1992. (Spring AGU, Montreal, Canada)

Erlandson, R. E., L. J. Zanetti, T. L. Aggson, and J. A. Slavin, Deposition of electromagnetic ion cyclotron wave energy into the ionosphere, AGU Chapman Conference on the Upper Mesosphere and Lower Thermosphere, November 1992.

Erlandson, R. E., T. L. Aggson, J. A. Slavin, Ionospheric signatures of electromagnetic ion cyclotron waves recorded by DE-2 near the plasmapause, EOS, Transactions, American Geophysical Union, 73, 467, 1992. (Fall AGU, San Francisco)

Erlandson, R. E., T. L. Aggson, W. R. Hoegy, and J. A. Slavin, Simultaneous DE-2 observations of subauroral electron enhancements and ion cyclotron waves, International Association of Aeronomy and Geophysics, 1993.

Erlandson, R. E., T. L. Aggson, and J. A. Slavin, DE-2 observations of electron acceleration and heating by EMIC waves at subauroral latitudes, Fall American Geophysical Meeting, 1993.

Erlandson, R. E., T. L. Aggson, and J. A. Slavin, Initial results from a statistical survey of Pc 1 waves recorded at ionospheric altitudes, Spring American Geophysical Union Meeting, 1994.

Erlandson, R. E., T. L. Aggson, J. A. Slavin, R. A. Hoffman, Thermal electron heating by ion cyclotron waves: DE-2 observations, COSPAR, 1994.

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SIMULTANEOUS OBSERVATIONS OF SUBAURORAL ELECTRON TEMPERATURE ENHANCEMENTS AND ELECTROMAGNETIC ION CYCLOTRON WAVES

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Abstract. Observational results from an investigation of low frequency (0.5-4.0 Hz) electromagnetic ion cyclotron waves and subauroral electron temperature enhancements recorded from the DE-2 satellite are presented. Four different wave events were analyzed, all recorded at magnetic latitudes from 57–60°, magnetic local times from 8–14 hours, and altitudes from 600–900 km. The peak wave amplitudes during the events ranged from 8–70 nT and 5–30 mV/m in the magnetic and electric field, respectively. Electron temperature (T_e) enhancements at the time of the waves were observed in 3 of 4 events. A linear relationship between the wave magnetic field spectral density and T_e enhancements was found for these events. The T_e enhancements were also correlated with an enhanced flux of low energy electrons. During one event (82104) an enhanced flux of electrons were observed at energies up to 50eV and at nearly all pitch angles, although the flux was largest in the precipitating and upflowing directions. It is suggested that the waves are responsible for heating the low energy electrons which precipitate to the ionosphere and produce the observed T_e enhancements. The upflowing electron population appears to be heated at ionospheric altitudes, below the DE-2 satellite. The precipitating electrons may also be heated at ionospheric altitudes through Landau damping, although the observations do not rule out electron heating near the equator.

1. Introduction

This paper investigates the role of electromagnetic ion cyclotron (EMIC) waves in thermal electron heating on field lines associated with subauroral electron temperature enhancements. Subauroral electron temperature (T_e) enhancements produce stable auroral red (SAR) arcs when the peak in T_e exceed a certain threshold [Chandra et al., 1971]. The energy source of T_e enhancements and the associated SAR arcs have been identified as ultimately coming from the ring current although the process of energy transfer from the ring current to thermal electrons is still under debate [Brace et al., 1967; Kozyra et al., 1986]. It has been shown theoretically that thermal electrons could be heated near the equator by Landau damping of oblique EMIC waves to temperatures sufficient to produce observable SAR arcs [Cornwall et al., 1971; Hasegawa and Mima, 1978; Thorne and Horne, 1992]. However, at the present time no observational evidence of EMIC waves and SAR arcs or T_e enhancements have been found. As a result, electron heating mechanisms which do not involve EMIC waves, such as Coulomb collisions between ring current ions and plasmaspheric electrons, is the most plausible mechanism used to explain T_e enhancements and the associated SAR arcs [Cole, 1965; Kozyra et al., 1987].

Low energy precipitating electrons have been observed over SAR arcs with a field-aligned flow velocity of 275 km/s and a temperature of approximately 1 eV [Gurgiolo et al., 1982]. Slater et al. [1987] conducted a study comparing ground based measurements of SAR arc emissions and DE-2 low energy electron observations, finding that the downward flux of low energy (<10 eV) electrons were enhanced on field lines penetrating the arcs. Model results indicate that this low energy electron population is sufficient to heat the ionospheric electron gas to temperatures which excite the observed 6300 Å SAR arc emissions [Slater et al., 1987]. The absence of higher energy electrons is consistent with the spectral purity of most SAR arcs. However, in a limited number of SAR arcs low levels of 5577Å and 4278Å emissions have been observed, suggesting that electron energies up to at least 18 eV must be present in these cases [Hoch, 1973].

EMIC waves are generated by proton temperature anisotropies in the energy range from 5–100 keV and at frequencies below the proton gyrofrequency which generally cover the Pc 1 frequency range in the Earth's magnetosphere (0.2–5 Hz). The EMIC wave frequency structure below the H^+ gyrofrequency is controlled primarily by the concentration of heavy ions (He^+ and O^+) in the thermal plasma and in the energetic ions which provide the free energy for the waves [Kozyra et al., 1984]. Large amplitude Pc 1 waves (5–30 nT) with a narrow spatial extent (<100 km) have been observed at ionosphere altitudes (350 km) near 60° invariant latitude using data acquired by the Magsat satellite [Iyemori and Hayashi, 1989]. In this paper we report on simultaneous observations of EMIC waves, low energy electrons, and T_e enhancements at subauroral latitudes using data acquired by DE-2.

2. Observations

This investigation used data acquired by the vector electric field instrument (VEFI), magnetometer (MAG-B), Low Altitude Plasma Instrument (LAPI), and Langmuir Probe (LANG) on the polar orbiting DE-2 satellite. VEFI used a double probe technique with a sampling rate of 16 Hz and resolution of ±0.1 mV/m. The two electric field components acquired by VEFI include the E_x component, directed along the satellite velocity vector (geographic north–south), and the E_y component, directed in the radial direction. The MAG-B instrument used a tri-axial fluxgate sensor to sample the vector magnetic field at a rate of 16 Hz with a resolution of ±1.5 nT. MAG-B data were transformed into a Geomagnetic Spherical (GMS) coordinate system, where B_R is radial outward, B_{th} is positive southward, and B_{phi} is positive eastward. The LAPI instrument recorded energy spectra in a time of 1s and contained 15 electron and 15 ion detectors oriented at different pitch angles. The electron temperature (T_e), electron density (n_e), ion density (n_i), and satellite potential are derived from Langmuir probe data at 4 s intervals.

This study uses four EMIC wave events which were identified in an initial inspection of full time resolution VEFI data. These events, summarized in Table 1, were chosen in that they were isolated from the fluctuations which are routinely observed in the auroral zone. The events all happened to be located on the dayside and in a narrow latitude range from 57–60° magnetic latitude (MLAT). It is stressed, however, that a more detailed survey of the data is required before the latitude and local time dependence of EMIC waves at ionospheric altitudes can be determined. In this case study, however, data from two of the four events are presented (day 82104 and 82214) while the other two events are briefly summarized.

The first event discussed in this paper was recorded on day

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TABLE 1. DE-2 Low Frequency Wave Events

Day	Time (UT)	MLAT	MLT (h)	Altitude (km)	Kp	Dst (nT)
81304	1215:45–1216:05	58.5°	8.6	910	2–	–12
82104	1252:02–1252:12	59.0°	9.3	690	1+	–8
82106	0913:35–0914:00	60.0°	10.3	680	1+	–9
82214	0550:08–0550:20	57.8°	13.6	595	4–	–41

82104 (Figure 1). Figure 1 shows the simultaneous observation of magnetic and electric field fluctuations, T_e enhancement, and enhanced low energy electron flux from 1252:02–1252:12 UT. The peak wave amplitude was observed at almost exactly the same time as the T_e enhancement and low energy electron flux. The dominant wave frequencies ranged from 0.5–3.5 Hz, which corresponds to frequencies both below and above the equatorial helium gyrofrequency ($f_{Heteq)}$) at L = 3.7. The Poynting flux, calculated using the E_x and B_{phi} components, reached 2 mW/m^2 and was directed downward. The polarization of these fluctuations were linearly polarized. The angle of the wave magnetic field with respect to the total magnetic field, was 70° from 1252:04–1252:08 and 80° from 1252:08–1252:11 UT. This indicates that the waves have a significant compressional component.

The differential number flux of precipitating electrons (12°) and upflowing electrons (167°) in the energy channels centered on 5.1, 8.8, 15, 27, and 48 eV are shown in the bottom panels of Figure 1. An increase in flux, above the background flux due to photoelectrons on either side of the event, was also observed at intermediate pitch angles (46–135°), although the flux was largest at 12° and 167°. The enhanced flux at 5.1 and 8.8 eV was observed throughout the entire 7s duration of the event while the flux from 15–48 eV was observed only during two energy sweeps coincident with the peak electron temperature and largest amplitude waves. Electron energy spectra of the differential number flux averaged from 1252:05–1252:08 UT and the background photoelectron flux outside of the event averaged from 1252:00–1252:02 UT at pitch angles of 12.9° and 167° are shown in Figure 2. The electron energy spectra, after subtracting the background photoelectron flux, may be fit using a low energy population with a temperature on the order of 1 eV and a higher temperature population with a temperature of 10 eV and drift energy of 15 eV. The low energy population was observed at pitch angles of 12°, 47°, 61°, 114°, and 167° but not at 135° pitch angle. The absence of this population at 135° pitch angle is not presently understood.

The higher temperature population was observed at all pitch angles, with the largest flux recorded at pitch angles of 12° and 167° (Figure 2). This higher temperature flux was observed for only 2 seconds (two energy sweeps) during the most intense wave activity from 1252:06–1252:07 UT. The higher temperature electron population was not observed in the events studied by Gurgiolo et al. [1982] and Slater et al. [1987].

The second event discussed in this paper was recorded on day 82214 (Figure 3). Waves were recorded from 0550:08–0550:20 UT while an enhancement in T_e and a small enhancement in the 5 and 9 eV precipitating electron flux (not shown) was observed from only 0554:14–0554:16 UT. The peak in T_e at 0554:14 UT occurred at the same time as the change in wave polarization and orientation (see B_R and B_{th} components). On the other hand, significant fluctuations were recorded in the B_{phi} component from 0550:10 to 0550:14 UT which were not correlated with the T_e enhancement. This may be an indication that the polarization and/or the orientation of the fluctuation is a factor in electron heating. The frequency range of the fluctuations was between 0.5–2.0 Hz, below $f_{Heteq)}$ at L = 3.6. The Poynting flux, determined using E_x and B_{phi}, was directed downward towards the Earth.

The third event studied in this paper was recorded on day 82106 from 0913:33 to 0913:55 UT. The wave amplitudes recorded during this event were approximately 5 nT (3 mV/m) from 0913:33–

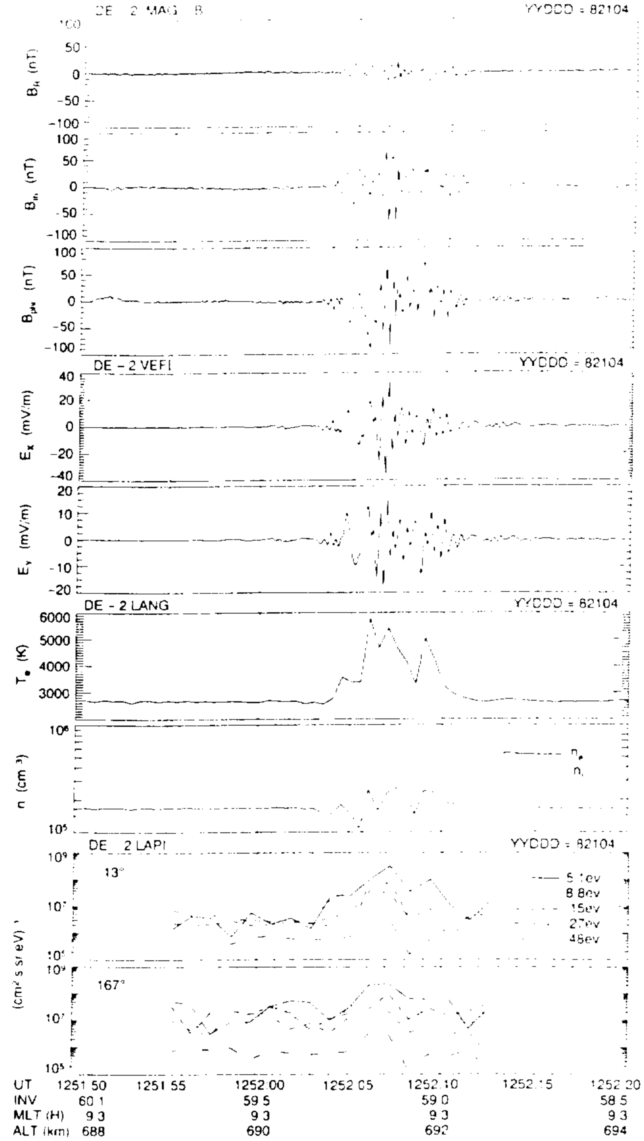

Fig. 1. MAG-B, VEFI, LANG, and LAPI electron differential number flux data on day 82104. The bottom two panels contain LAPI data from 5–48 eV at 13° and 167° pitch angle.

0913:50 UT and 25 nT (18 mV/m) from 0913:46–0913:48 UT in the magnetic (electric) field. A T_e enhancement of 600K was recorded during this event from 0913:33–0933:36 UT, shifted by about 10s from the peak wave amplitude. The lack of correlation during this event may have been the result of a movement of the wave source region just prior to the observation.

The fourth wave event in this study was recorded on day 81304. The waves recorded on this day were lower in amplitude than the other events. The peak amplitude in the magnetic and electric field was 8 nT and 5 mV/m, respectively. There was no enhancement in T_e above the base value of 3200K or low energy electron flux recorded during this event.

3. Discussion

The source of the large amplitude magnetic and electric field fluctuations recorded by DE-2 is consistent with the EMIC wave mode generated in the equatorial magnetosphere. However, there were a number of unusual features. For example, the wave amplitudes were unusually large, reaching 70 nT in the magnetic field and 30 mV/m in the electric field. Waves with large amplitudes (5–30 nT), in the same frequency range, and at the same latitudes (57–60°) have been recorded by Magsat [Iyemori and Hayashi, 1989]. It is noted, however, that EMIC wave amplitudes

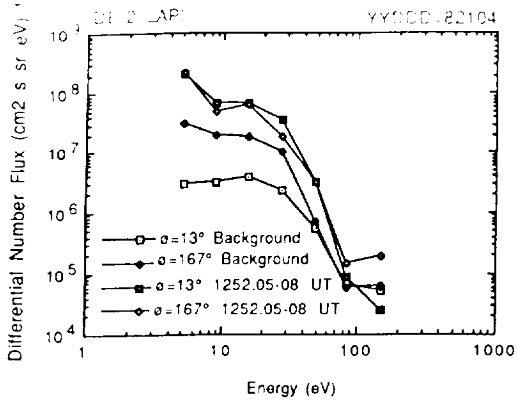

Fig. 2. LAPI electron energy spectra during the EMIC wave event (1252:05–1252:08 UT) and just prior to the event (1252:00–1252:02 UT) on day 82104. The spectra is shown for pitch angles of ø=13° and ø=167°.

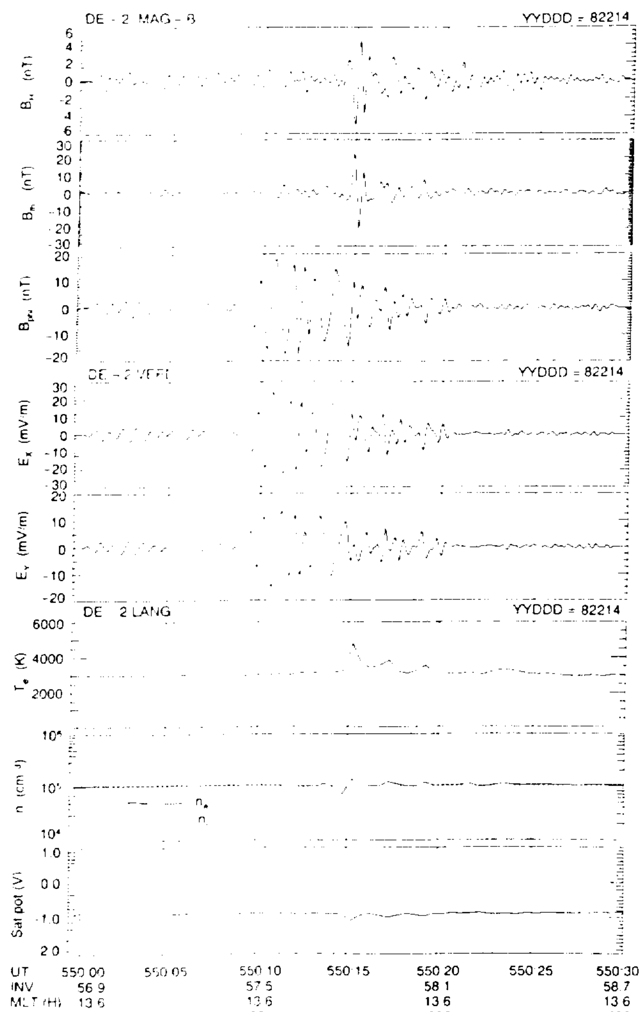

Fig. 3. Overview of data acquired by MAG-B, VEFI, and LANG from 0549–0559 UT on day 82214.

are typically on the order of 1 nT near the equator [Anderson et al., 1992]. A second unusual feature of these waves was the significant compressional component (direction parallel to the Earth's magnetic field, $\mathbf{B}_o$). This was particularly clear during the event recorded on day 82104, where the wave magnetic field was linearly polarized and oriented at an angle of 70° from $\mathbf{B}_o$, with amplitudes reaching 20 nT in the compressional component from 1252:03–1252:08 UT. The properties of the observed waves are nearly identical to those predicted by Denton et al. [1992] for EMIC waves generated with linear polarization by a proton loss-cone-driven instability. Furthermore, the estimates in Figure 8 of Denton et al. [1992] indicate that the waves observed on day 82104 were oblique with a wave vector of ≈65° from $\mathbf{B}_o$.

The relationship between EMIC waves and T_e enhancements are investigated using the four events listed in Table 1 by comparing the wave spectral density and magnitude of the T_e enhancement (Figure 4). The spectral density was estimated using the magnetic field since all three components were available. The spectral density was calculated using consecutive Fast Fourier Transforms (FFTs) of 40 points representing 2.5 s of data. The window of data to which the FFTs were applied was shifted by 24 points for each new FFT. The spectral density for each magnetic field component was averaged over the frequency range from 0.2–3.4 Hz and then summed. The T_e data were interpolated to times of the mid-point of each FFT. A linear interpolation was used. The time intervals used in the correlation extended for a time period of about 1 minute centered on the peak in T_e. The electron temperatures were normalized so that the electron temperature on either side of the peak was approximately 2700 K.

A linear relationship was found between the magnetic field spectral density (U_b) and electron temperature enhancement (ΔT_e). A functional form, $\Delta T_e = 2720 + 2.16U_b$, was found, with a correlation coefficient of 0.88 where ΔT_e is in units of (K) and U_b in units of (nT^2/Hz). The electron heating is negligible below 100 nT^2/Hz which corresponds to wave amplitudes of about 20 nT over the frequency range from 0.2–3.4 Hz (Figure 4). It is cautioned, however, that the functional dependence depends heavily on one event (day 82104). The functional dependence may explain the lack of T_e enhancement during the event on day 81304, where a maximum amplitude was only 8 nT.

The peak EMIC wave energy flux, determined using the B_{phi} and E_x components, associated with T_e enhancements during 3 of the 4 events, were in the range from 0.1–2.0 mW/m^2. This wave energy flux is directed downward and is therefore available as an energy source for electron heating at ionospheric altitudes. The energy flux required to produce dayside electron temperatures between 3000–6000K under steady state conditions is in the range from 0.001 to 0.01 mW/m^2 [Khazanov et al., 1992; see Table II]. Therefore, the EMIC wave energy flux observed during these events warrants consideration of electron heating through a Landau damping process at ionospheric altitudes.

The low energy electron flux (≈1 eV) observed in this study are very similar to the fluxes reported by Gurgiolo et al. [1982] and Slater et al. [1987], although there are some important differences in the pitch angle distribution. The primary differences are that on day 82104 significant fluxes of low energy electrons were observed at pitch angles up to 114° as well as upflowing electrons at 167°. It is possible that these electrons are heated at the equator through Landau damping of oblique EMIC waves [Cornwall et al., 1971; Thorne and Horne, 1992] or by a similar mechanism at ionospheric altitudes. Landau damping increases the parallel energy of the electrons but it is thought that non-resonant processes, such as collisions, maintain approximate pitch angle isotropy [Cornwall et al., 1971]. Energies of electrons heated through Landau damping are on the order of 0.1–1 eV, based on the resonance condition of $v_a = 2V_{Te}$, where V_{Te} is the electron thermal velocity [Hasegawa and Mima, 1978]. If these electrons precipitate to the ionosphere and mirror below the DE-2 altitude then this mechanism is consistent with some of the features of the observed low energy (≈1 eV) electron population. Landau damping of electrons at the equator does not explain, however, the enhanced flux of upward moving electrons at 167° pitch angles. The source of these upflowing electrons is presently unknown, although these observations suggest that the electrons are heated by EMIC waves at ionospheric altitudes. In fact, some of the waves recorded by DE-2 in the ionosphere had large wave normal angles and therefore might be Landau damped in the ionosphere. The resonance condition for Landau damping, $v_a = 2V_{Te}$, is satisfied

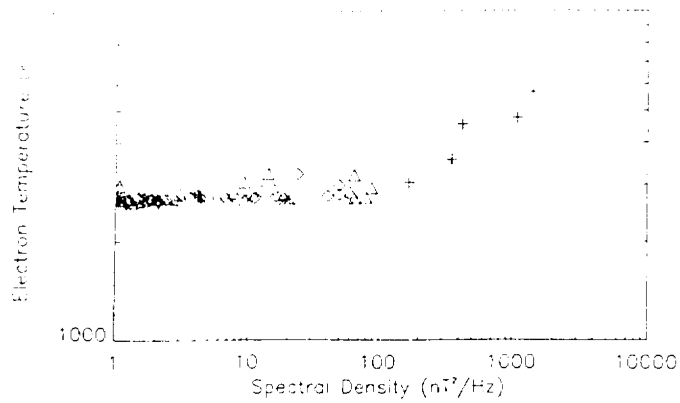

Fig. 4. Dependence T_e on the magnetic field spectral density from 0.2–3.4 Hz. The data are from the events on days 81304 (*), 82104 (+), 82106 (◊), and 82214 (Δ).

in the ionosphere, where the Alfven velocity reaches a minimum.

The higher temperature electron population, with a temperature of 10 eV and a drift energy of 15 eV observed on day 82104, appears to be a feature associated with extremely large amplitude EMIC waves. This distribution had a maximum flux at 12 and 167° pitch angle and a minimum near 90°, although the flux at all pitch angles were above the background flux due to photoelectrons. If this event is associated with SAR arcs then this electron population may be related to a small subset of SAR arc (6300Å) observations accompanied by low levels of 5577Å and 4278Å emissions which require electron energies of 18 eV [Hoch, 1973]. The pitch angle distribution of these electrons imply that the electrons were accelerated and heated at altitudes above the DE-2 satellite. It is interesting to note that enhanced field-aligned fluxes of electrons in this energy range (≈20 eV) have been observed together with EMIC waves near the equator [Mauk and McPherron, 1980; Norris et al., 1983; Roux et al., 1984].

4. Summary

These observations suggest that EMIC waves are responsible for heating low energy electrons which precipitate to the ionosphere and produce the observed T_e enhancements. The upflowing electron population appear to require electron heating at ionospheric altitudes, below the DE-2 satellite. In fact, the precipitating electrons and electrons at intermediate pitch angles may also be heated by EMIC waves at ionospheric altitudes through a Landau damping mechanism. On the other hand, the observations do not rule out electron heating near the equator.

The observations here raise a number of questions as to the limitations and extent of EMIC wave electron heating associated with T_e enhancements. First, are EMIC waves associated with all or just a subset of ionospheric T_e enhancements? If EMIC waves occur in only some cases, then under what conditions? Are the events studied in this paper representative of typical T_e enhancements? Further studies involving more events are needed to fully characterize the statistical properties of EMIC waves and subauroral T_e enhancements.

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