Multi-Ion, Multi-Event Test of Ion Cyclotron Resonance Heating

A Semiannual Status Report

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The multi-ion, multi-event study of ion cyclotron resonance heating has been funded to study ion energization through ion cyclotron resonance with low frequency broadband electromagnetic turbulence. The modelling algorithm for the ion cyclotron resonance heating (ICRH) of oxygen ions was presented in Crew et al. (1990). Crew and his co-authors developed a two-parameter representation of selected oxygen conic distributions and modelled the conic formation in terms of resonance heating. The first year of this study seeks to extend the work of Crew and his co-authors by testing the applicability of the ICRH mechanism to helium ion conic distributions, using data obtained from the Energetic Ion Composition Spectrometer and the Plasma Wave Instrument on Dynamics Explorer 1.

A Study of the Ion Cyclotron Resonance Heating of Helium Conic Distributions: The First Eight Months

Work began as soon as funding became available on May 8, 1993. Dr. Wei Feng assumed the position of programmer and began coordinating efforts to transfer the analysis and simulation software developed by Geoff Crew and John Retterer for the 1990 study of the cyclotron resonance heating of oxygen conics. Dr. Feng worked with Dr. Retterer in successfully completing the transfer of the software and was responsible for installing and adapting the software to run on the SUN workstations at the University of Iowa. The software packages which analyze the data and derive the appropriate parameters for the simulation were modified only slightly to adapt the software to the computer systems at the University of Iowa. Some up-dates were made in the orbit-attitude data with particular attention to the most recent Dynamics Explorer spin vector information.

In addition to completing the modifications on the analysis software, Dr. Feng also developed display software for the wave and particle data. He completed work on a plot program to display the electric field spectral density and power-law fitting code (see Figure 3, included) and worked on a plot program to display the EICS helium ion distribution in velocity phase space. Further work on the ion distribution plot program (Figure 1) was continued by a new programmer, Dr. Julie Dowell, when Dr. Feng left the University of Iowa in September.

Dr. John Retterer modified the analysis software to handle the helium ion data. He also developed a comprehensive plot package to display the frequency-time spectrogram of the low frequency electric field data, both in full time resolution and averaged over integral numbers of spin periods (Figures 2 and 4), and the plots of the velocity scaling and pitch angle scaling parameters calculated from the wave and particle data (Figures 5 and 6). At

this time, all of the display software provided by Dr. Retterer has been installed on the SUN workstations at the University of Iowa. Dr. Retterer also provided plots of the simulated ion distribution, derived from the modelling algorithm (Figure 7).

The wave and ion data, which was published in the 1990 study of the cyclotron resonance heating of oxygen ion conics, was used to test the analysis and display software. Plots of the oxygen ion distribution and the scaling parameters for the modelling algorithm, generated at the University of Iowa, were found to compare with those published in Crew et al. (1990). A similar analysis was performed on a selected helium ion event from Day 47, 1982 and the results were presented in a poster session at the Fall AGU meeting on December 10. A copy of the poster paper is included with this report. The application of a cyclotron resonance heating mechanism to the particle and wave data for this event indicates that the helium conic observed at 1851 UT has been produced via a cyclotron resonance heating process.

Tasks Remaining:

We are currently working on several modifications to the display software which would improve the intensity scaling of the observed ion contour plot in order to produce a plot of publishable quality. We will also adjust the grey scales on the observed and simulated ion distribution plots so that the two scales are comparable.

We are now completing the analysis of several additional helium conic events as a further test of the applicability of the ICRH mechanism to the helium ion species. A paper is in progress and will be submitted to the Journal of Geophysical Research in February, 1994.

References:

G. B. Crew, Tom Chang, J. M. Retterer, W. K. Peterson, D. A. Gurnett, and R. L. Huff, Ion cyclotron resonance heated conics: Theory and observations, J. Geophys. Res., 95, 3959, 1990.

A TEST OF THE ION CYCLOTRON RESONANCE HEATING MECHANISM FOR HELIUM ION CONICS

by

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A TEST OF THE ION CYCLOTRON RESONANCE HEATING MECHANISM FOR HELIUM ION CONICS

Ion conics are characterized by velocity space distributions which have significant intensity maxima in a cone-shaped region centered on the magnetic field line. These distributions are thought to be created by the localized transfer of energy to a cool plasma. A number of theoretical models have been proposed to account for the transverse heating of these ion populations. One of these, the ion cyclotron resonance heating (ICRH) mechanism, explains ion conic formation through ion cyclotron resonance with electromagnetic plasma turbulence. Crew et al. (1990) successfully developed an algorithm to apply the ICRH mechanism to the heating of oxygen ions along auroral field lines. In this paper we test the applicability of the ICRH mechanism to a second ion species, using data obtained from the Energetic Ion Composition Spectrometer (EICS) and the Plasma Wave Instrument (PWI) on Dynamics Explorer 1. The algorithms developed by Crew et al. (1990) are applied to a classic example of an energetic helium conic distribution on Day 47, 1982. We test the success of the ICRH theory by modelling this helium conic formation in terms of a resonant wave-particle interaction in which the helium ions extract energy from the portion of the electric field turbulence which includes the helium cyclotron frequency.

Figure 1 is a contour plot of the helium ion distribution derived from the EICS data for the 90-second interval beginning at 18:51 UT. The EICS instrument was configured in the slow mode for this pass and requires 15 spin periods, or 90 seconds, to span all 15 energy steps and obtain a complete measurement of the velocity space. Figure 1 represents a transformation of the observed ion distribution from the measurement plane in spacecraft coordinates to the velocity phase space of parallel and perpendicular velocity components. As the Dynamics Explorer spacecraft passes through the nightside auroral region, several cone-shaped helium distributions are observed. This particular event is well-correlated with increases in the power of the waves observed by the PWI.
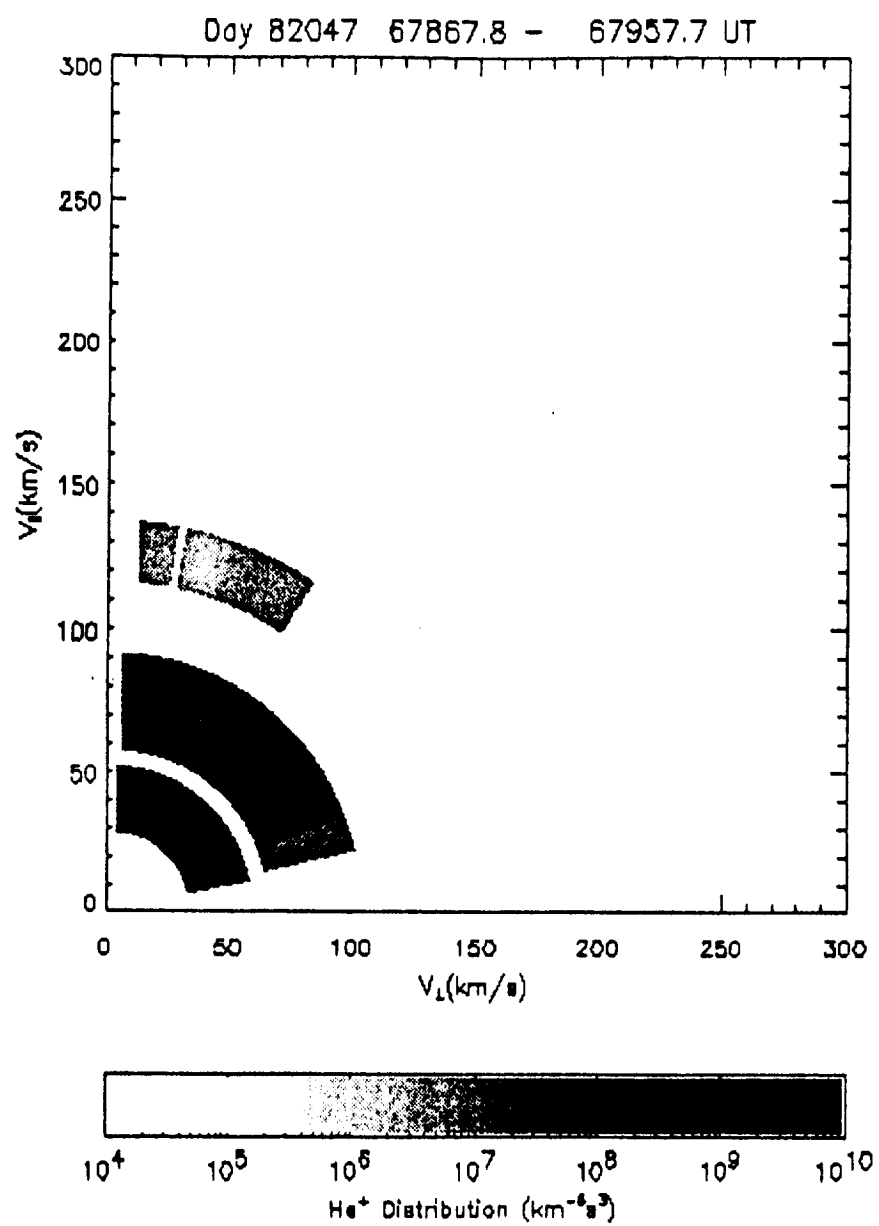
Day 82047   67867.8 -   67957.7 UT

Figure 1

Low-frequency electric field data in the helium cyclotron frequency range is sampled by the DC portion of the PWI at a rate of 16 samples/second. The spectrum measurements are, for analysis purposes, an average over the parallel and perpendicular components of the waves with respect to the magnetic field. The ICRH theory predicts that the helium ions will interact with the left-hand polarized portion of the wave spectrum in the helium cyclotron frequency range. The left-hand polarized component of the low-frequency spectrum will be modelled as some undetermined fraction η of the observed spectral density along the flux tube.

Figure 2 is the gray scale frequency-time spectrogram and contour plot of the PWI DC electric field spectra at full time resolution, one spectrum per satellite spin, for a 15-minute time interval beginning at 18:42 UT. The spectra are calculated using the maximum entropy technique with a five pole approximation. The maximum entropy technique is used because the technique is better able to resolve sharp spectral features and produces a spectrum which is smoother and less noisy than the spectrum produced by the fast Fourier transform method. The results are evaluated at frequency intervals of $\frac{1}{3}$ Hz up to the Nyquist frequency of 8 Hz. Contour levels of the spectral density (in V^2/m^2-Hz) are at powers of ten. The helium cyclotron frequency varies from 2.4 Hz to 2.9 Hz across the time interval. Peaks in the wave activity at 18:44 UT and 18:50 UT are highly correlated with the observance of conic distributions in the helium data.

DE-1 Day 82047 18:42 UT

$S_E \ [(V/m)^2/Hz]$

10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8}

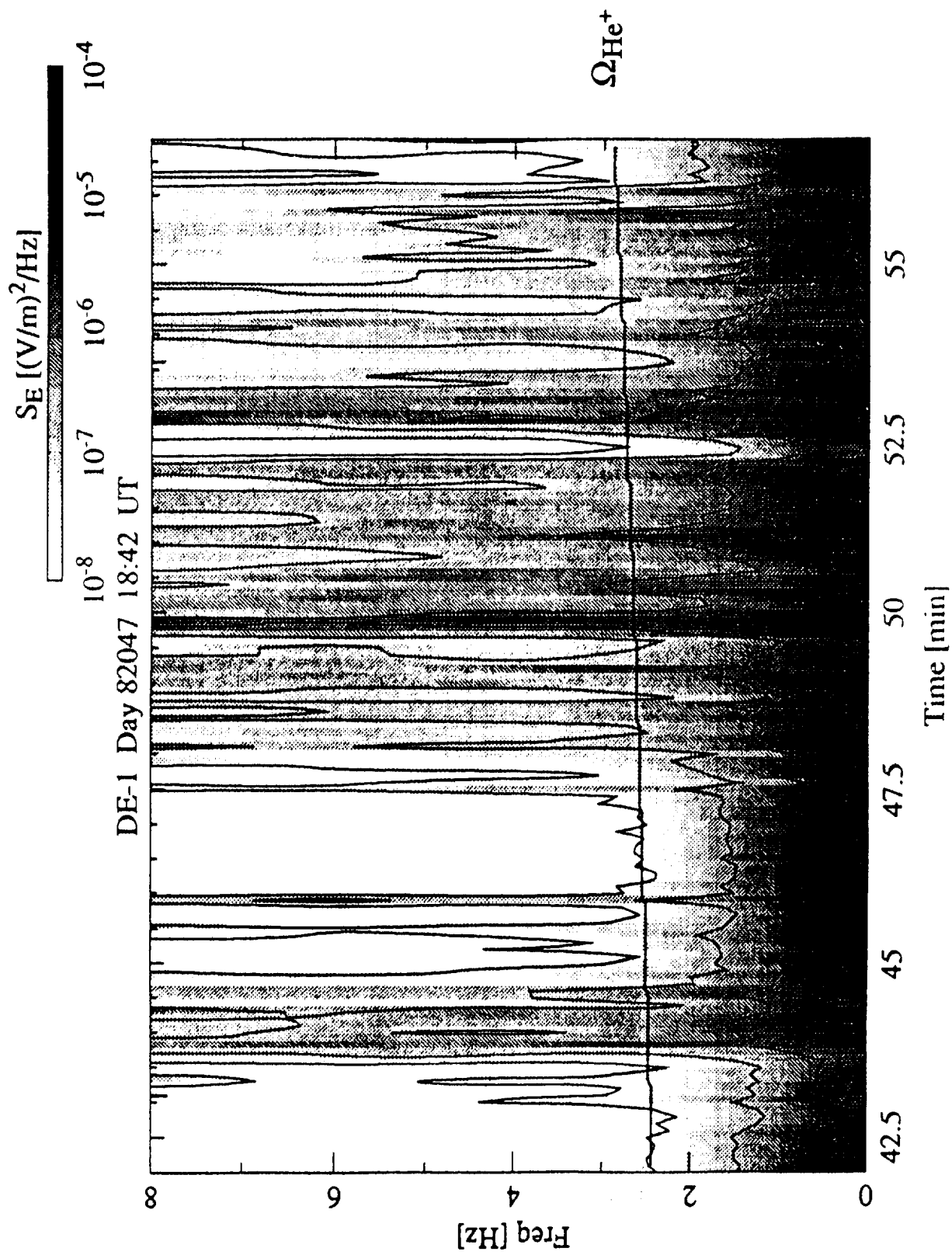Ω_{He^+}

Freq [Hz]

Time [min]

Figure 2

Figure 3 illustrates the increase in the power of the low frequency waves which correlates with the observance of the helium conic distribution shown in Figure 1. The two panels in Figure 3 show the DC electric field spectral density for four satellite spins at 18:48:59 UT (Figure 3a) and 18:51:01 UT (Figure 3b). The dashed line represents the power-law fit to the four DC spectra in each panel. The spectral index α, derived from the slope of the line, is -1.20 just prior to the conic event (Figure 3a) and -1.94 at the time of the observed conic (Figure 3b). The spectral index and wave spectral density are used as input parameters for the modelling algorithm.

Figure 4 is the gray scale and contour plot of the fitted power-law spectra for the electric fields shown in Figure 2. This figure has been derived using running means over eight satellite spins to reduce the scatter of the data points. A comparison of the fitted power-law spectra with the electric field spectrum at full time resolution in Figure 2 confirms the validity of these power-law fits which are used to extract the scaling parameters for the ICRH theory.
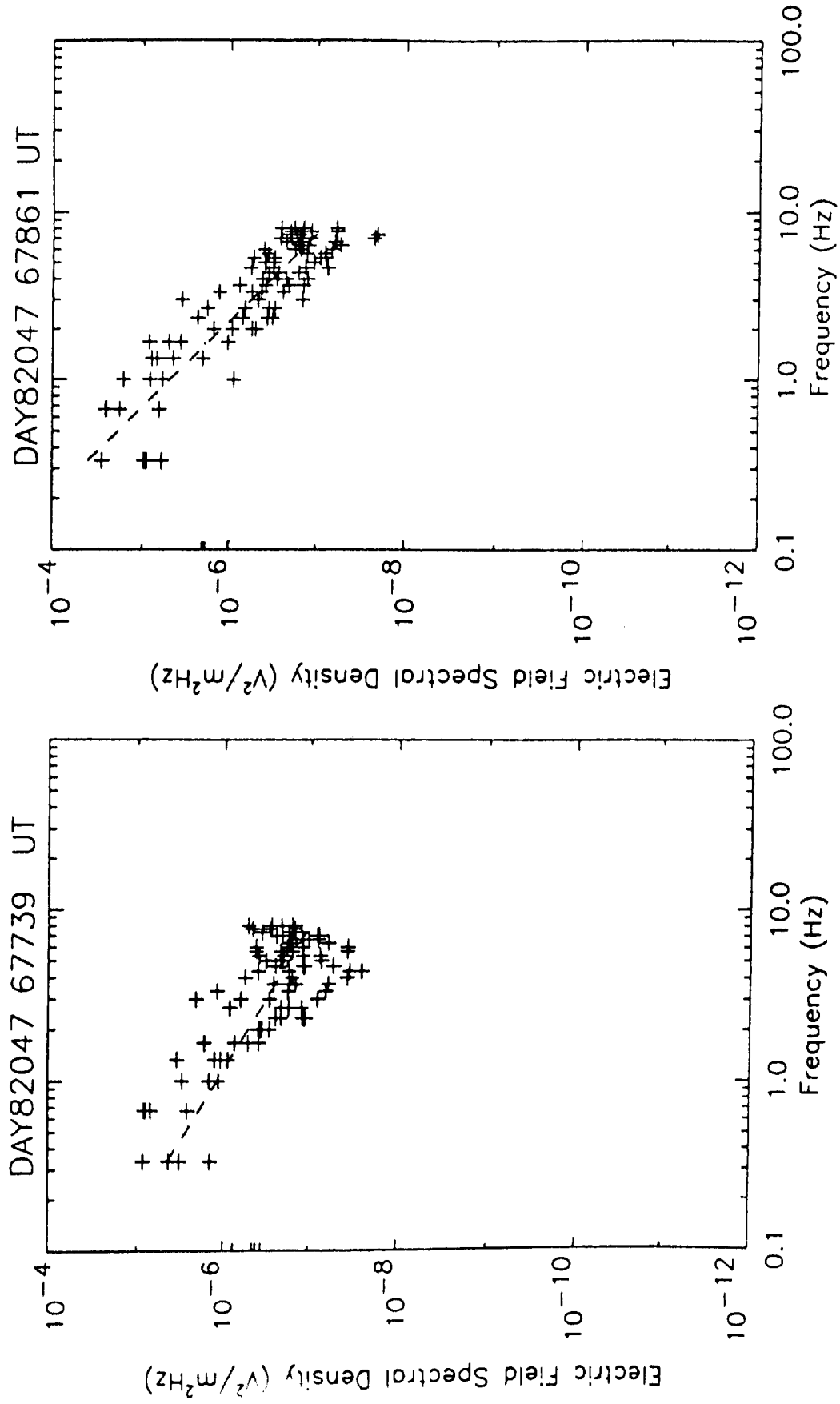
DAY82047 67861 UT

Electric Field Spectral Density (V^2/m^2Hz)

Frequency (Hz)

Figure 3b

DAY82047 67739 UT

Electric Field Spectral Density (V^2/m^2Hz)
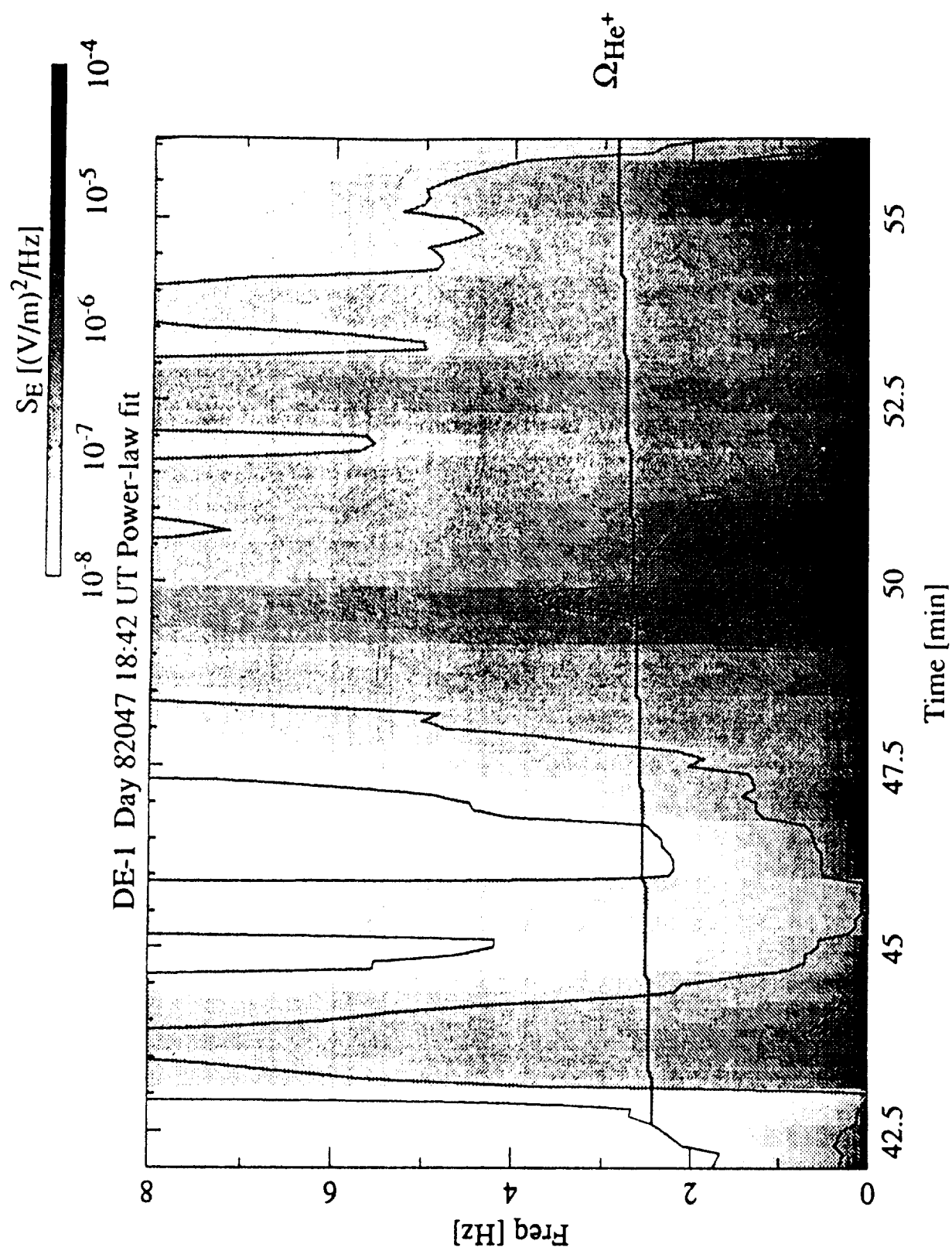
Frequency (Hz)

Figure 3a

Figure 4

To model the formation of the ion conic in terms of ion cyclotron resonance heating, a Monte Carlo technique is used. The ion, moving up the flux tube, interacts with the left-hand polarized waves in a narrow frequency band near the local ion cyclotron frequency. The action of the wave turbulence is modelled by a sequence of random velocity increments resulting in velocity space diffusion. The observed wave spectrum is related to the strength of the diffusion by:

$$D_\perp = (q^2/4m^2) \, |E_L|^2 \, f_{ci} \qquad \text{(Eq. 1)}$$

where f_{ci} is the local cyclotron frequency (in Hz) and E_L is the left-hand polarized component of the wave spectrum. This component will be represented as an undetermined fractional component of the observed wave spectrum, $\eta |E|^2$. Both the electric field spectral density and the local cyclotron frequency have power-law dependences. The electric field spectral density is represented as a power-law function of frequency $|E|^2(\omega) \alpha \ \omega^{-\alpha}$ where α is the spectral index. The cyclotron frequency, because of the power-law variation of the magnetic field with altitude, is represented as a power-law function of altitude, varying as $(\ell/\ell_o)^{-3}$. The resulting form of the diffusion coefficient is:

$$D_\perp = D_o \, (\ell/\ell_o)^{3\alpha} \qquad \text{(Eq. 2)}$$

where $\qquad D_o = (\eta q^2/4m^2) \, |E|^2 \, f_{ci} \qquad \text{(Eq. 3)}$

Crew et al. (1990) found that the Monte Carlo simulation produced results which were insensitive to the characteristics of the initial distribution, because the diffusion and mirror forces acting on the ions would rapidly re-form the distribution into a conic shape that remained constant as the ions moved up the flux tube. With this type of self-similar evolution of the ion distribution, the characteristics of the initial unknown distribution can be ignored. Solutions to the moment equation (Equation 11 in Crew et al., 1990) are sought which vary as $(\ell/\ell_o)^\sigma$ in the same manner as the magnetic field and diffusion coefficient vary. This scaling constraint is achieved only for:

$$\sigma = (3\alpha + 1)/3 \qquad \text{(Eq. 4)}$$

where σ is the scaling parameter which defines the shape of the conic and α is the spectral index of the low frequency turbulence. This scaling constraint on the individual moments converts the moment equation into a three-term recursion relation among the moments of the distribution which are entirely determined by two parameters, σ and v_o. The velocity scaling parameter v_o is defined by:

$$v_o = (D_o\, \ell_o)^{1/3} \qquad \text{(Eq. 5)}$$

where the diffusion coefficient D_o is given by Equation 3. For a more complete discussion of the modelling algorithm, please refer to Crew et al. (1990) and the references therein.

Relations among an infinite set of moments are now entirely characterized by two scaling parameters which can be independently determined from the EICS and PWI data and used to illustrate the temporal variations encountered as the spacecraft moves across different flux tubes. PWI observations allow a direct determination of the sigma parameter from Equation 4 and, with an approximation for the fractional left-hand polarized component of the wave spectrum, an indirect determination of the velocity scaling parameter from Equation 5. The time series of both scaling parameters derived from the PWI data are shown in Figures 5 and 6, respectively, for a 15-minute time interval beginning at 18:42 UT. The fraction of left-hand circularly polarized waves in the low frequency spectrum, η, is approximated to be 0.25, a reasonable value which gives the best match between the velocity scale calculated from the ion data and the velocity scale inferred from the wave data. In these figures, each point represents an average over eight satellite spins. At 18:51 UT, the PWI observations give a σ scaling parameter of 1.6 and a velocity scaling parameter of approximately 82 km/sec.
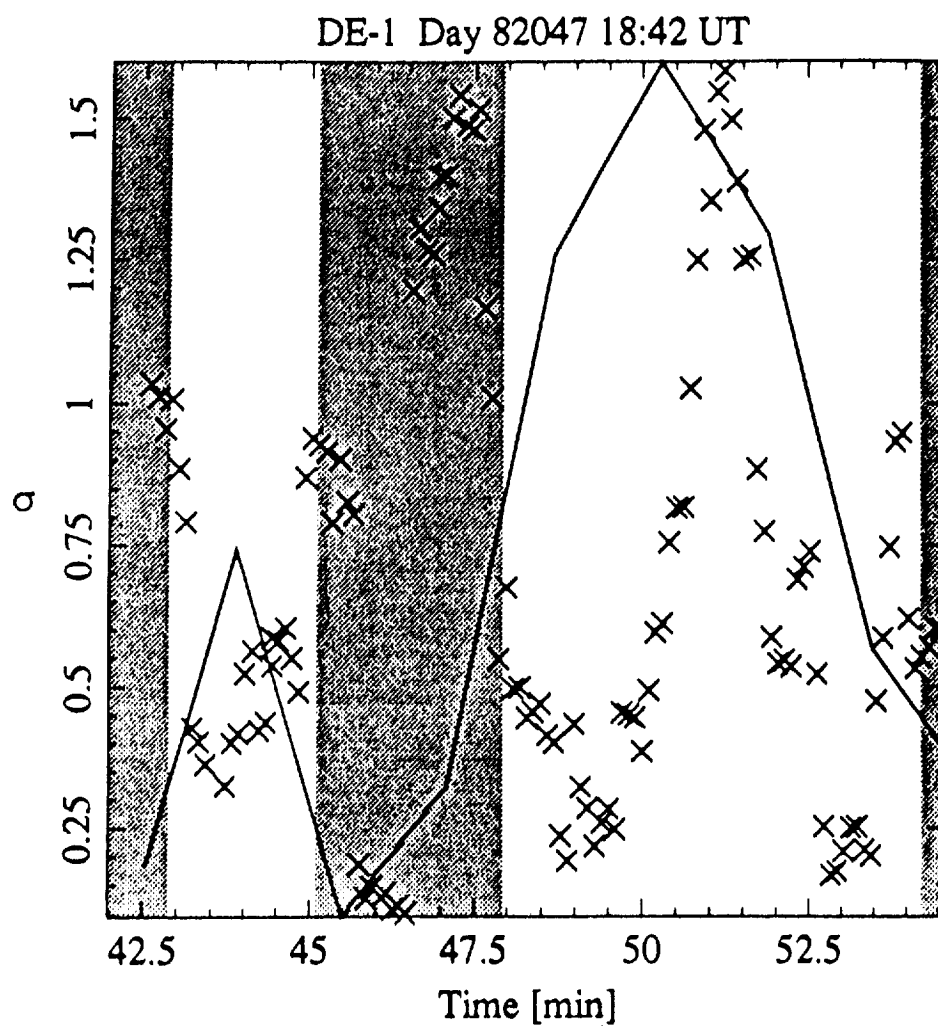
Figure 5

DE-1 Day 82047 18:42 UT $\eta = 0.25$
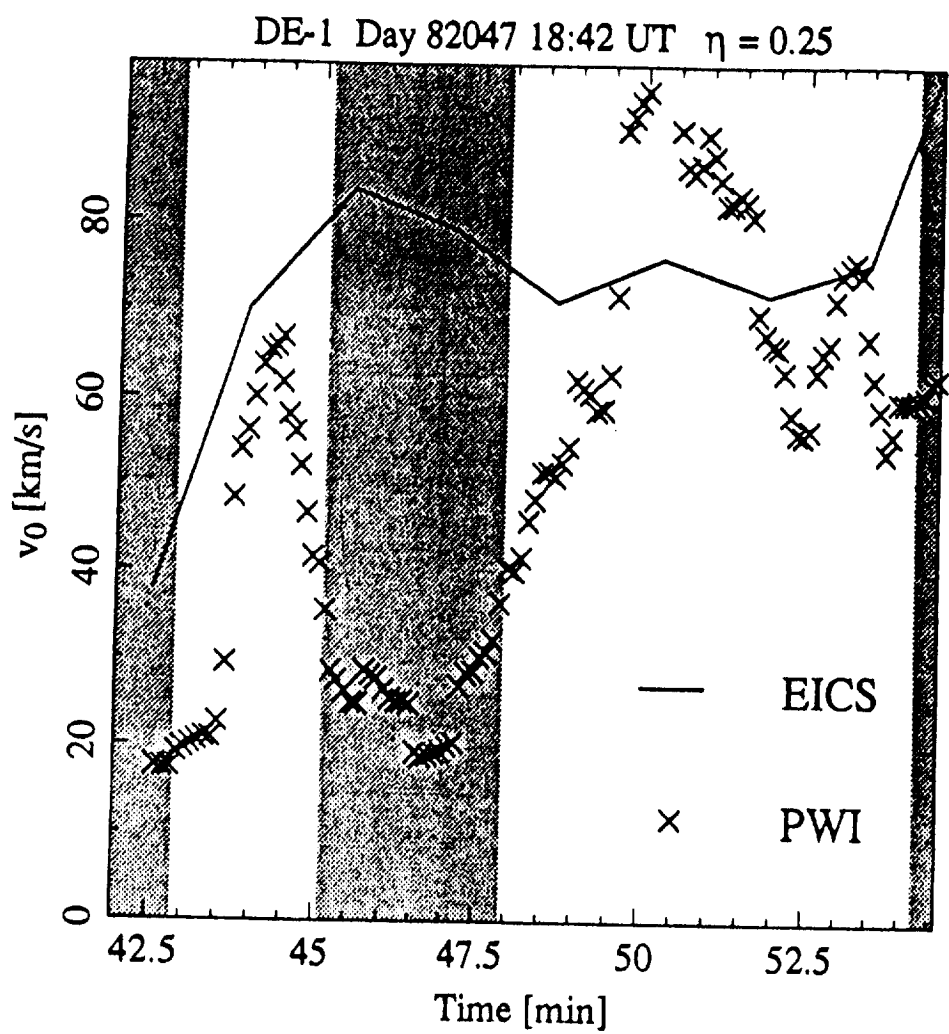
EICS

× PWI

Figure 6

To obtain the scaling parameters from the EICS observations, the recursion relation (Equation 27 in Crew et al., 1990) is solved for a finite set of moments, each of which gives a linear relation in σ and v_o. The two scaling parameters are obtained from a least squares fit to these linear relations. Figures 5 and 6 show the σ and the velocity scaling factors calculated from the moments of the ion distribution (solid line). Fifteen satellite spins, or 90 seconds, were required to span all 15 energy steps in the ion distribution. The parameter shown in Figure 5 determines the shape of the ion conic and is indirectly inferred from the ion data through the ratio of different velocity moments. The velocity scaling parameter shown in Figure 6 describes the velocity scale of the helium conic distribution at 4.2 R_E in the nightside auroral zone near local midnight. At 18:51 UT, the σ parameter derived from the EICS data is 1.5 and the velocity scaling parameter is approximately 74 km/sec.

In comparing the wave and particle data, we find that there is correspondence between the PWI and EICS scaling parameters only when the electric field amplitudes and ion fluxes are both large. In Figures 5 and 6, intervals of significant ion flux are highlighted and intervals of low flux occur in the shaded areas. Both the wave and ion scaling parameters tend toward a climax just after 18:50 UT and the values for the parameters calculated from the ion moments are in reasonable agreement with those predicted by the PWI instrument.

The ICRH theory predicts that the low frequency turbulence measured by the PWI should produce a conic of a particular form. The final test of the theory then is to compare the observed ion distribution with the modelled distribution, derived from the moments of the ion distribution and the calculated scaling parameters. Figure 7 shows the results of a Monte Carlo simulation run at 18:51 UT. PWI data from 18:51 UT was used to set the input parameters for the simulation code: a spectral index of -1.5 (derived from running means over eight satellite spins), an electric field spectral density of $2.5 \ e^{-6}$ (V^2/m^2-Hz) at unit frequency (half the peak value of the spectral density at 18:51 UT), a helium cyclotron frequency of 2.6 Hz and a fractional component of the left-hand circularly polarized waves in the low frequency wave spectrum of 0.25 (η).

The conic distribution based on numerical solutions compares favorably with the observed distribution in Figure 1. Both distributions peak just below $v_\parallel = 50$ km/sec as $v_\perp$ goes to 0. However, the $v_\perp$ extent of the contours in the observed distribution is comparable to the extent of the contours in the simulated distribution only for the darker regions denoting greatest phase space density. This discrepancy is due to the fact that the helium ion data comprising the conic distribution is from the two lowest energy channels of the EICS instrument. Although there is qualitative correspondence between the observed and simulated distributions, there is no quantitative correspondence between the contour/halftone representations in Figures 1 and 7.
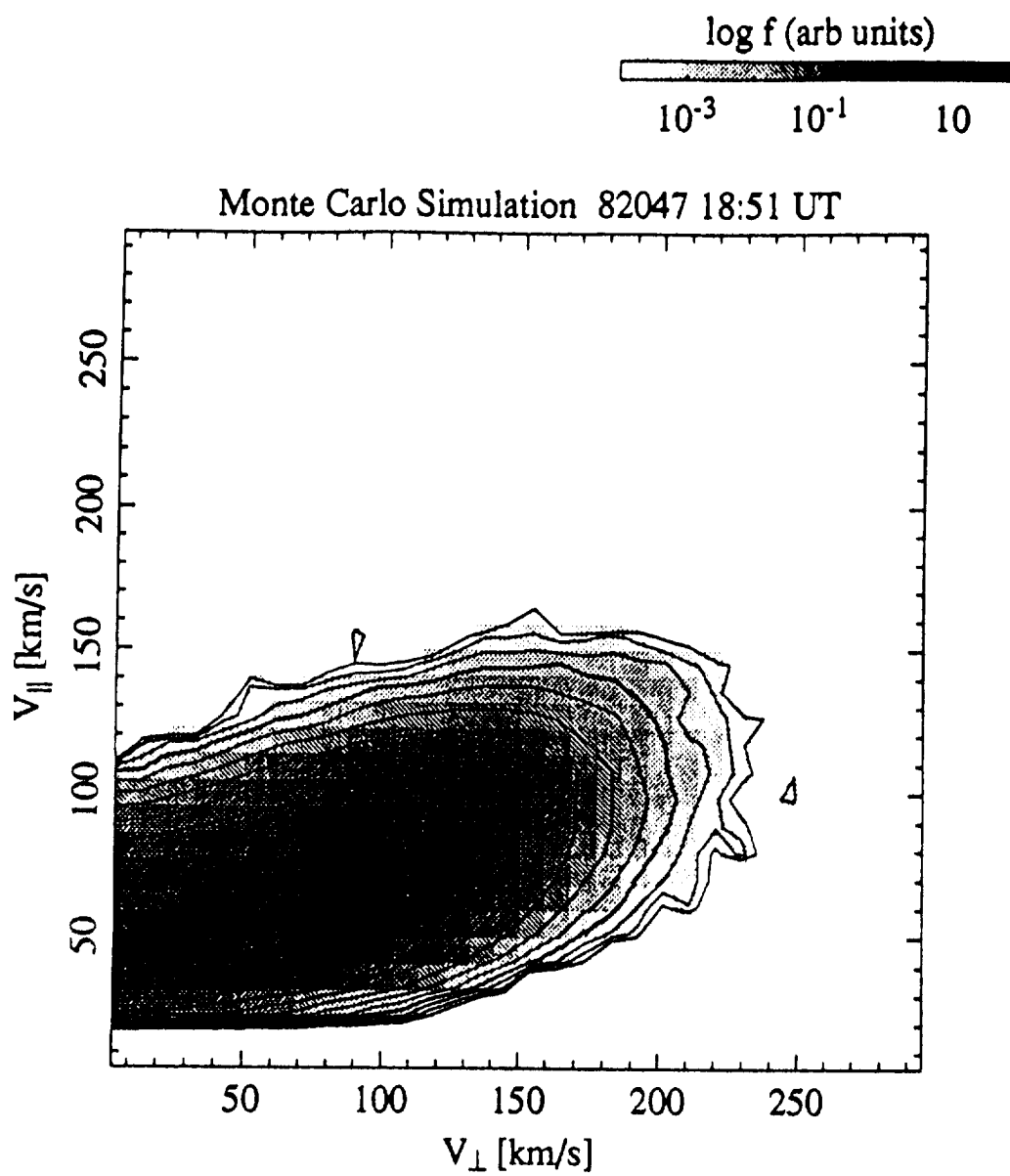
log f (arb units)

10^{-3} 10^{-1} 10

Monte Carlo Simulation 82047 18:51 UT

Figure 7

SUMMARY

The correlation between the scaling parameters determined independently from the EICS and PWI data are convincing evidence that the helium conic observed at 18:51 UT on 82047 has been produced via a cyclotron resonance heating process. The time series evolution of the scaling parameters indicates that these separately determined parameters all tend toward climax near 18:51 UT and that the parameters calculated from the moments of the observed ion distribution fall within the range of values predicted by the PWI observations. Furthermore, there is a similar time series evolution observed in the wave activity and the low frequency electromagnetic turbulence required for conic generation is present at adequate intensities. Finally, the correspondence between the observed conic distribution and the velocity space form of the simulated distribution derived from the modelling algorithm is evidence that this ion conic distribution is an ICRH conic.

Crew, G. B., Tom Chang, J. M. Retterer, W. K. Peterson, D. A. Gurnett, and R. L. Huff, Ion cyclotron resonance heated conics: Theory and observations, J. Geophys. Res., 95, 3959, 1990.