JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. A2, PAGES 1353–1361, FEBRUARY 1, 1992

Association of Electron Conical Distributions With Upper Hybrid Waves

J. D. MENIETTI, C. S. LIN, AND H. K. WONG

Department of Space Sciences, Southwest Research Institute, San Antonio, Texas

A. BAHNSEN

Danish Space Research Institute, Lyngby, Denmark

D. A. GURNETT

Department of Physics and Astronomy, University of Iowa, Iowa City

The particle and plasma wave data of the DE 1 and Swedish Viking satellites shows that intense (>1 mV/m) upper hybrid emissions are sometimes present in the mid-altitude polar magnetosphere on both the dayside cusp/cleft and the nightside auroral regions and that waves near the upper hybrid frequency are often associated with electron conical distributions. These observations are consistent with the production of at least some electron conical distributions by oblique heating of the electrons by upper hybrid waves. Examination of the wave data to establish the role of parallel heating remains to be performed.

INTRODUCTION

A number of papers have recently appeared discussing the generation mechanisms for electron conical distributions since their discovery in the DE 1 data set [*Menietti and Burch*, 1985]. *Menietti and Burch* [1985], who observed the electron conics associated with trapped particles and parallel electric fields, suggested a wave-particle interaction and perpendicular heating as a source mechanism, in analogy with ion conic formation. *Lundin et al.* [1987] and *Hultqvist et al.* [1988] have reported observations of electron conics in the Viking data and suggested that a parallel potential that varied in magnitude over a fraction of an electron bounce period might explain electron conics that were observed associated with ion conics. Using plasma parameters indicative of the mid-altitude nightside auroral region as observed on DE 1, *Wong et al.* [1988] have shown that upper hybrid waves generated by a loss cone distribution can heat the electrons oblique to the magnetic field. They pointed out, however, that any other particle distribution that produced $df/dv_\perp > 0$ might also act as the free energy source. Subsequently, numerical simulations of the production of electron conics by upper hybrid waves using a loss cone [*Roth et al.*, 1990] and a loss cone with a ring distribution [*Lin et al.*, 1990; *Menietti et al.*, 1990] have been performed. *Swift and Gorney* [1989] have shown by particle simulation that electron beams in the presence of density gradients perpendicular to the magnetic field can excite upper hybrid waves.

Roth et al. [1990] and most recently *Temerin and Cravens* [1990] (extending the ideas of *Lundin et al.* [1987]) have demonstrated that an electron conical distribution can result from parallel heating of the electrons via electrostatic or acoustic mode waves. Upon mirroring, this heated electron distribution resembles the conical distributions presented by *Menietti and Burch* [1985]. *Menietti and Borovsky* [1989] have independently demonstrated the effectiveness of parallel heating of electrons via beam-generated electrostatic waves (strongly magnetized Langmuir waves). Subsequently, *Temerin and Cravens* [1990] have demonstrated with a test particle simulation of the electron distribution that electron conics can be produced purely by stochastic acceleration of the electrons parallel to a dipole magnetic field. Temerin and Cravens have pointed out that an extensive survey of strong narrow-banded emissions at higher frequencies conducted by *Beghin et al.* [1989] found many cases of Landau resonant interactions and waves near the plasma frequency but none near the upper hybrid frequency. The study conducted by Beghin et al. was performed using data from the AUREOL/ARCAD 3 satellite at high latitude and at altitudes between 400 and 2000 km. *Temerin and Cravens* [1990] thus suggested that parallel acceleration of electrons could be accomplished by Alfven-ion cyclotron waves which have been observed in association with inverted-V electron precipitation [*Gurnett and Frank*, 1972; *Temerin and Lysak*, 1984; *Gustafsson et al.*, 1990].

Temerin and Cravens [1990] conducted independent simulations of parallel-only acceleration and perpendicular-only acceleration by stochastic processes. They point out that the resulting model contours of the electron distribution function can be distinguished from one another and that those produced by strictly parallel acceleration are better representations of the actual data presented by *Menietti and Burch* [1985]. It was pointed out by *Wong et al.* [1988], however, that because of the dependence of the diffusion coefficient on energy and pitch angle, upper hybrid waves heat the electrons both in the parallel and the perpendicular direction [cf. *Wong et al.*, 1988, Figures 2*a* and 2*b*]. In other words, upper hybrid waves were found to heat the electrons oblique to the magnetic field. In addition, *Temerin and Cravens* [1990] state that for the case of perpendicular heating, the resultant contours of the distribution reflect the fact that there are upgoing electrons at perpendicular velocities at which there are few corresponding downgoing electrons. By contrast, for the case of parallel acceleration only, the ratio of upgoing to downgoing electrons should always be one except in the case of lower energy backscattered electrons. However, for all of the electron conics observed for the pass

Paper number 91JA02392.
0148-0227/92/91JA-02392$05.00

of day 309 of 1981 [*Menietti and Burch*, 1985], for example, we calculate more particles detected moving up the field line than down. For this example, in the range 1.7 x 10^4 km/s $< V_\perp <$ 2.4 x 10^4 km/s which includes the electron conical distribution, the ratio n_{up}/n_{down} varied from $\gtrsim 1$ to 1.45.

The above studies have thus far demonstrated by theory and simulation that electron conics can be generated by upper hybrid waves (oblique heating) and/or by electron acoustic waves, Langmuir waves, or Alfven-ion cyclotron waves (parallel heating). A correlation of electron conics with plasma wave and particle data remains to be shown.

In this paper we present observations of both particle and plasma wave instruments on board DE 1 and the Swedish Viking satellite that demonstrate the presence of intense upper hybrid waves at midaltitudes of the polar magnetosphere. This is an interesting result in light of the observations of the AUREOL/ARCAD 3 satellite as reported by *Beghin et al.* [1989]. We will also show an association of waves near the upper hybrid frequency with electron conical distributions. This study is not a comprehensive statistical survey of all existing High Altitude Plasma Instrument (HAPI) data, which would be tedious and time consuming; it is, however, a careful survey of all of the easily accessible high resolution HAPI data that yielded about a dozen examples of electron conics. This work does not preclude the existence of parallel acceleration processes as the source of electron conics; it does, however, suggest that upper hybrid waves may heat electrons oblique to the magnetic field and these waves may be responsible for at least some of the observed electron conical distributions.

ASSOCIATION OF ELECTRON CONICS AND UPPER HYBRID WAVE OBSERVATIONS

Instrumentation

The Dynamics Explorer 1 satellite was launched into a high inclination polar orbit with an apogee of about 23,000 km and a perigee of about 650 km. On DE 1, the High Altitude Plasma Instrument (HAPI, J. L. Burch, Principal Investigator) has an energy range of 5 eV to 32 keV with an energy resolution of $\Delta E/E = 0.32$. The Plasma Wave Instrument (PWI, D. A. Gurnett, Principal Investigator) has a step frequency receiver with a frequency range of 2 Hz to 400 kHz. The Swedish Viking satellite was also launched into a polar orbit with high inclination but with a lower apogee of about 13,500 km and perigee of about 800 km. The spacecraft spins at 3 rpm. On Viking, the high-frequency wave instrument (V-4H, A. Bahnsen, Principal Investigator) has two step-frequency analyzers each with a frequency range of 9-512 kHz.

Observations

As pointed out by *Wong et al.* [1988] simultaneous observations of upper hybrid waves and electron conics in the source region might be expected. By assuming that electron conical distributions are formed at pitch angles of 90°, *Menietti and Burch* [1985] used conservation of the second adiabatic invariant to suggest that the source region for the electron conics observed by DE 1 is perhaps somewhere between 3000 and 6000 km. The DE 1 satellite observed the electron conics at altitudes greater than 10,000 km, so it was unclear whether or not correlations with upper hybrid waves should be expected in the DE data. The simulations performed by *Roth et al.* [1990] and *Lin et al.* [1990], however, using plasma parameters typical of DE 1 altitudes in the nightside auroral region, indicate that the conical distributions are formed outside of the loss cone at pitch angles of approximately 150° rather than at 90° confirming the oblique heating predicted by *Wong et al.* [1988]. Examination of a number of the DE 1 passes indicates an association of electron conical distributions and upper hybrid waves. In addition, as shown below, the Viking wave data include clear examples of upper hybrid waves in the midaltitude polar magnetosphere.

This report does not consititute a comprehensive study of all of the available data from the HAPI, but a preliminary examination of much of the data has been performed. A more comprehensive, statistical survey will be undertaken when resources become available. Of 12 orbits on which electron conics were observed, waves near the upper hybrid frequency were seen (within about 30 s) on 10 of them. In addition, we have also identified in the DE data two cases of upper hybrid waves that were not associated with electron conical distributions.

We consider four passes of the DE 1 instrument as exemplary of the associations observed. The days chosen are from 1981: day 281, 309, 278, and 261. The pass for day 81/281 is a nightside auroral region pass when the DE 1 spacecraft was at an altitude of about 10,670 km, invariant latitude, $\Lambda = 63.6°$, and magnetic local time, MLT = 21.18. Plate 1 is an energy-versus-time color spectrogram of the plasma data obtained by HAPI for the time interval 0731:30 to 0733. The electrons are shown in the top panel and ions in the bottom panel. The electrons show intense flux for energies $E > 1$ keV typical of a region of field-aligned potential in the boundary plasma sheet (BPS). The upward moving ions indicate that an upward electric field of several hundred eV exists below the satellite. In the electron data one can observe regions of enhanced energy flux lying just outside of the loss cone and extending to energies greater than 10 keV. These appear as red and yellow signatures at $E \gtrsim 3$ keV at times indicated by the arrows in Plate 1. These distributions look similar to those in Plate 2 of *Menietti and Burch* [1985] and identified as electron conics. Electron conics are often the most energetic electrons of the entire population (see Plate 1 of *Menietti and Burch* [1985]). In the example of Plate 1, the conical electrons are the most energetic at the highest intensity of energy flux. In Figures 1*a* and 1*b* we show contour plots of the velocity-space distribution function for electrons obtained during two separate time intervals. The plots were each compiled from data obtained from HAPI over one spin (approximately 6 s) of the DE 1 spacecraft. The data sampling times for each contour are labelled. The conics are enhancements of the distribution function outside the loss cone (seen in the bottom half of the plot for negative $v_\parallel$).

Figure 2 is a plot of the power spectral density (PSD) versus frequency using wave data obtained from the Plasma Wave Instrument (PWI) on board the DE 1 spacecraft. The time listed on the PSD plot is the start time of the 32-s frequency scan time. Note that the PWI data for the plot were sampled in the time between the times of the contour plots of Figure 1. The power spectral density generally decreases with frequency but has a narrow-banded peak at a frequency just above the gyrofrequency, $f_{ce} \sim 70$ kHz, and is therefore identified as upper hybrid emission. The gyrofrequency is indicated with a vertical dotted line. By direct integration

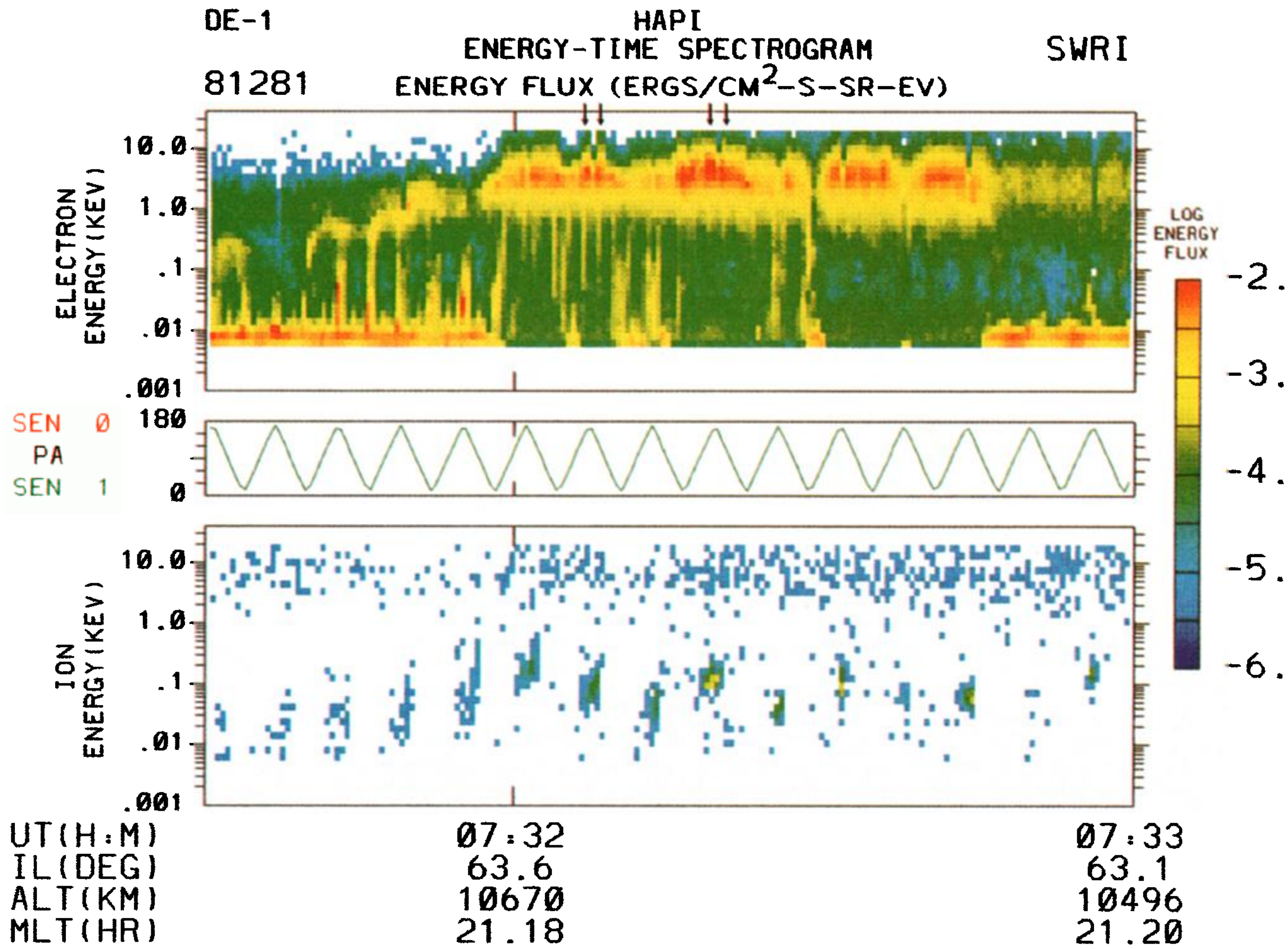


Plate 1. Energy-versus-time color spectrogram of HAPI electron and ion data with energy flux color-coded according to the color bar at the right. This is a nightside auroral region pass for day 281 of 1981.

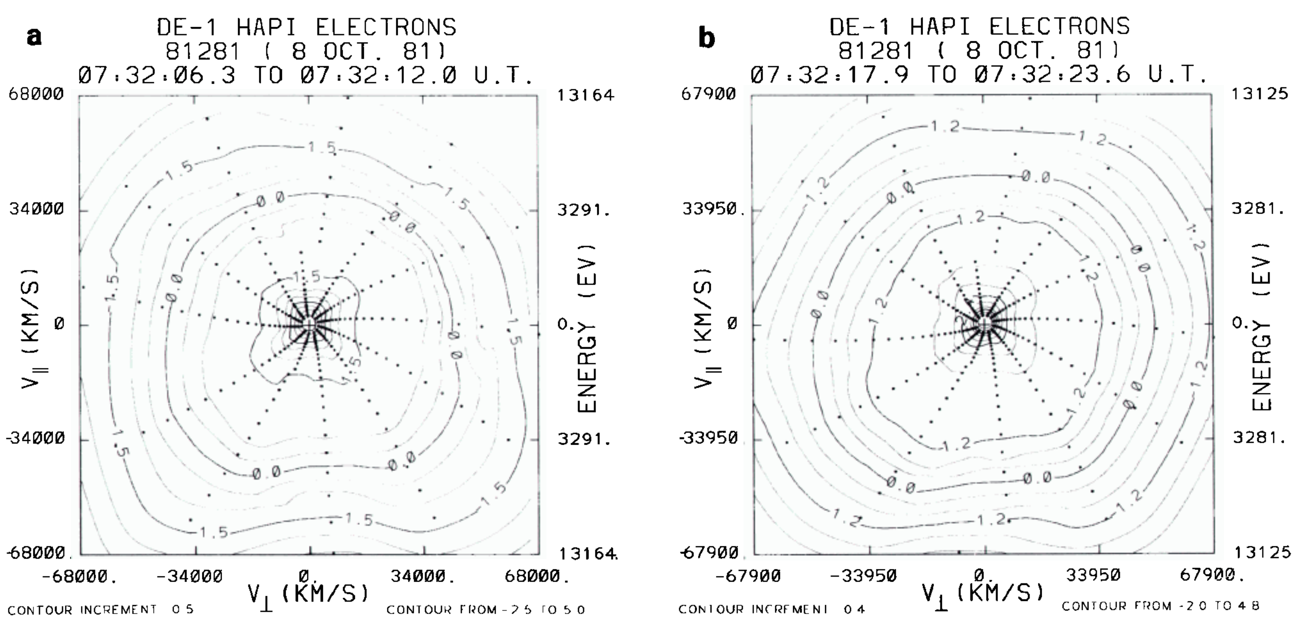


Fig. 1. Contours in velocity-space of the electron distribution function obtained during one spin of the DE 1 satellite for the pass of day 281 of 1981. The times are shown on each plot. The electron conical distribution appears as enhancements of the distribution function outside the loss cone.

of the plasma data obtained by HAPI, the plasma density was determined to be about 6.5 cm^{-3}, yielding a plasma frequency, $f_p \sim 23$ kHz. Since the upper hybrid frequency is defined as $f_{UH} = \sqrt{f_p^2 + f_{ce}^2}$, and $f_p \ll f_{ce}$, we expect $f_{UH} \sim f_{ce}$. The approximate electric field amplitude for the upper hybrid emission is 0.3 mV/m. Note that the upper hybrid emission is well above the ambient wave intensity. The magnetic field values used in identifying the gyrofrequency

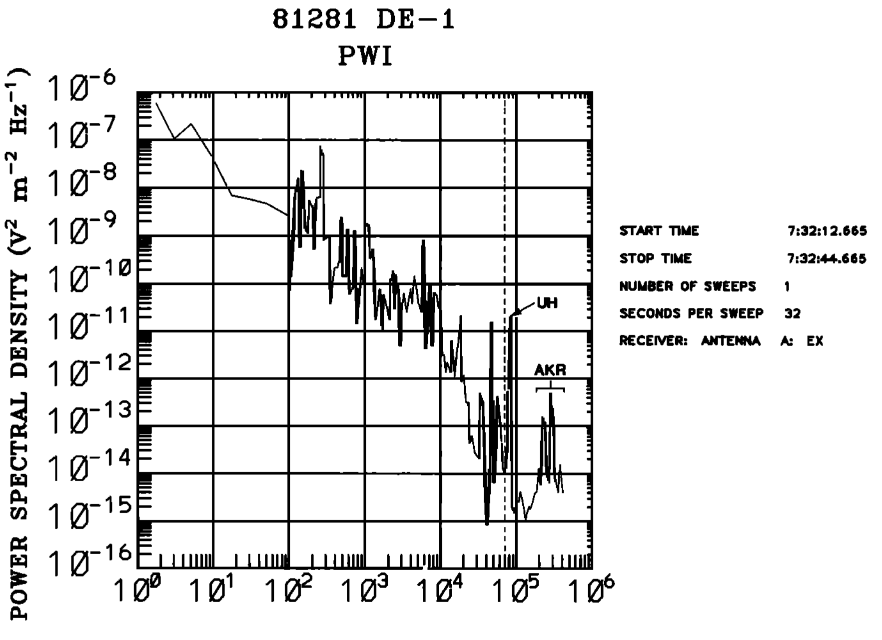


Fig. 2. Power spectral density versus frequency for the time interval overlapping that of Figures 1*a* and 1*b*. The gyrofrequency is indicated on this plot (and on all subsequent power spectral density plots) by a vertical dotted line. The peak believed to be upper hybrid emission is indicated just above the gyrofrequency.

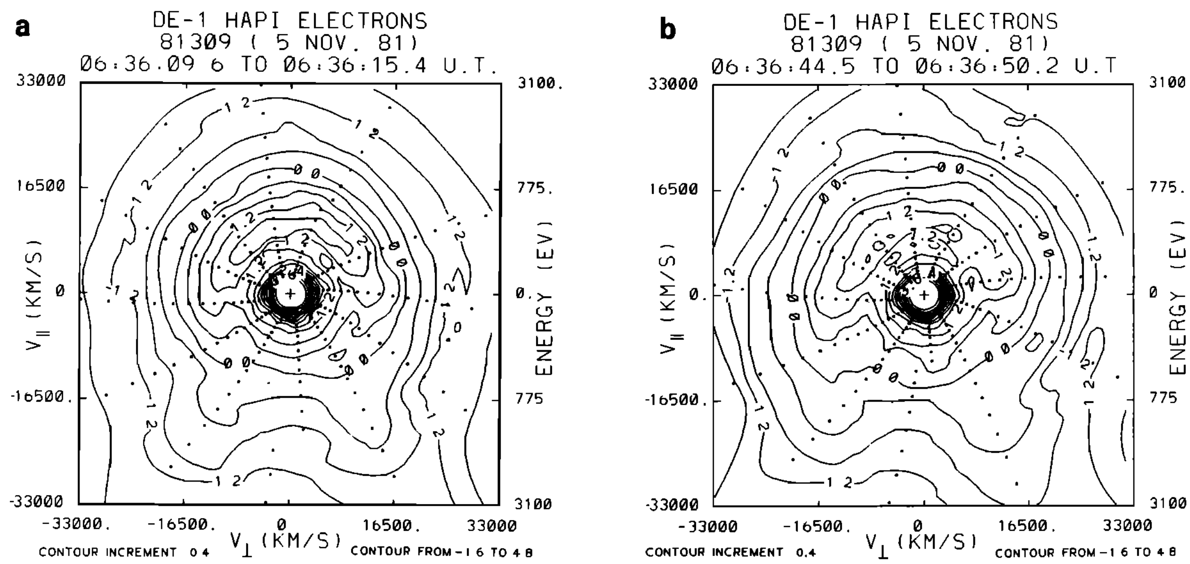


Fig. 3. Contours of the electron distribution function for the pass of day 309 of 1981. The plots were produced by sampling data over independent spins of the satellite (times indicated on the plot).

for all of the power spectral density plots of this paper were obtained from the Magsat model.

A color spectrogram of the particle data for the pass of day 81/309 was published as Plate 1 of *Menietti and Burch* [1985] and will not be reproduced here. Instead, in Figures 3*a* and 3*b* we show contours of the electron distribution function for the two time intervals indicated. These contours clearly display the electron conical signature of enhanced electron flux outside the upgoing loss cone. In Figures 4*a* and 4*b* we likewise display plots of the PSD obtained from the PWI data for time intervals which overlap those of Figures 3*a* and 3*b*. A relatively distinct peak just above the gyrofrequency occurs in each plot. The gyrofrequency was determined from the Magsat model as before to be about 78 kHz. Direct integration of the plasma data yields $f_p \sim 5$ kHz, so once again, $f_{ce} \sim f_{UH}$. The electric field intensity determined from Figures 4*a* and 4*b* is about 0.06 and 0.14 mV/m, respectively.

The next pass for consideration is 81/278. A series of electron conics occurred for this pass within the dayside cusp/cleft starting at about 1350:30. A contour of one of these conics is shown in Figure 5. About 1 min earlier on this pass a strong peak just above the gyrofrequency was detected by PWI. At the time of the electron conics, however, only a rather low intensity and broad peak occurs just less than the gyrofrequency. We show a series of three PSD plots depicting the sequence in Figures 6*a*, *b*, and *c*. First, the distinctive emission is near f_{ce} ($\sim$ 23 kHz) which we interpret

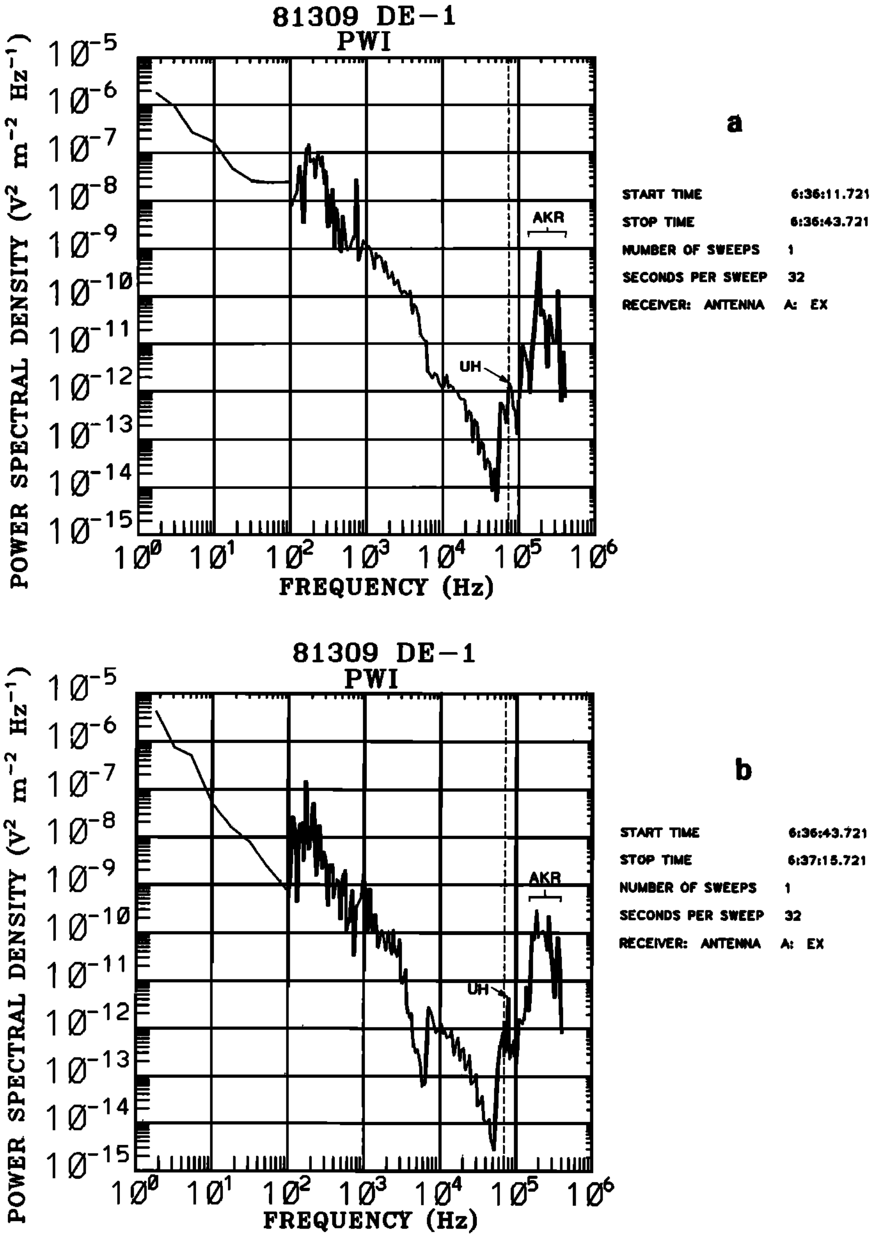


Fig. 4. Power spectral density versus frequency obtained during a period which overlaps the times when electron conics (Figure 3) were observed.

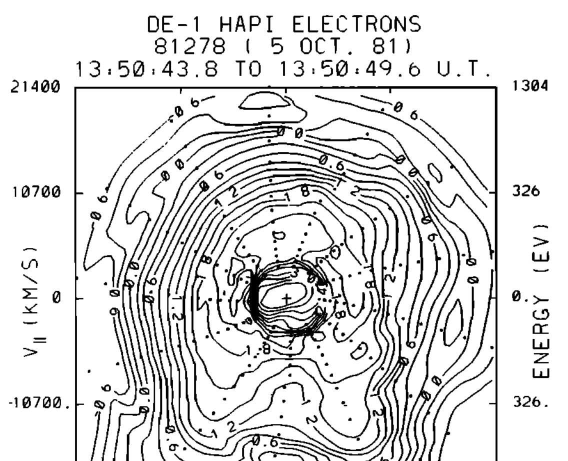


Fig. 5. Contour of the electron distribution function showing a conic for the dayside cusp/cleft pass of day 278 of 1981.

as an upper hybrid emission with electric field amplitude estimated at about 0.015 mV/m. The plasma frequency is estimated at about 6.5 kHz by direct integration of the plasma data. Figure 6*b* shows virtually no emission near f_{ce}, but in Figure 6*c* a rather broad, low-intensity peak is seen. The data for Figure 6*c* were obtained simultaneously with the observation of the series of three electron conics. We hypothesize that upper hybrid emissions may have been responsible for the generation of the electron conics; however, the satellite passed through the region just after the wave-particle interactions took place. *Wong et al.* [1988] have shown that the wave growth expected for upper hybrid waves generated from loss cones is typically $2 \times 10^{-4}/\Omega_{ce}$. For $f_{ce} \sim 23$ kHz, the time for one *e*-folding of the power is of the order of 0.02 s. Observations of the wave-particle interactions thus seem doubtful with currently orbiting satellites.

The final DE 1 example is that of a nightside auroral region pass for day 81/261. In Figure 7 we display a contour of the electron distribution function in velocity space. The data were obtained during two spins of the satellite (~12 s) and show an enhancement of flux just outside the loss

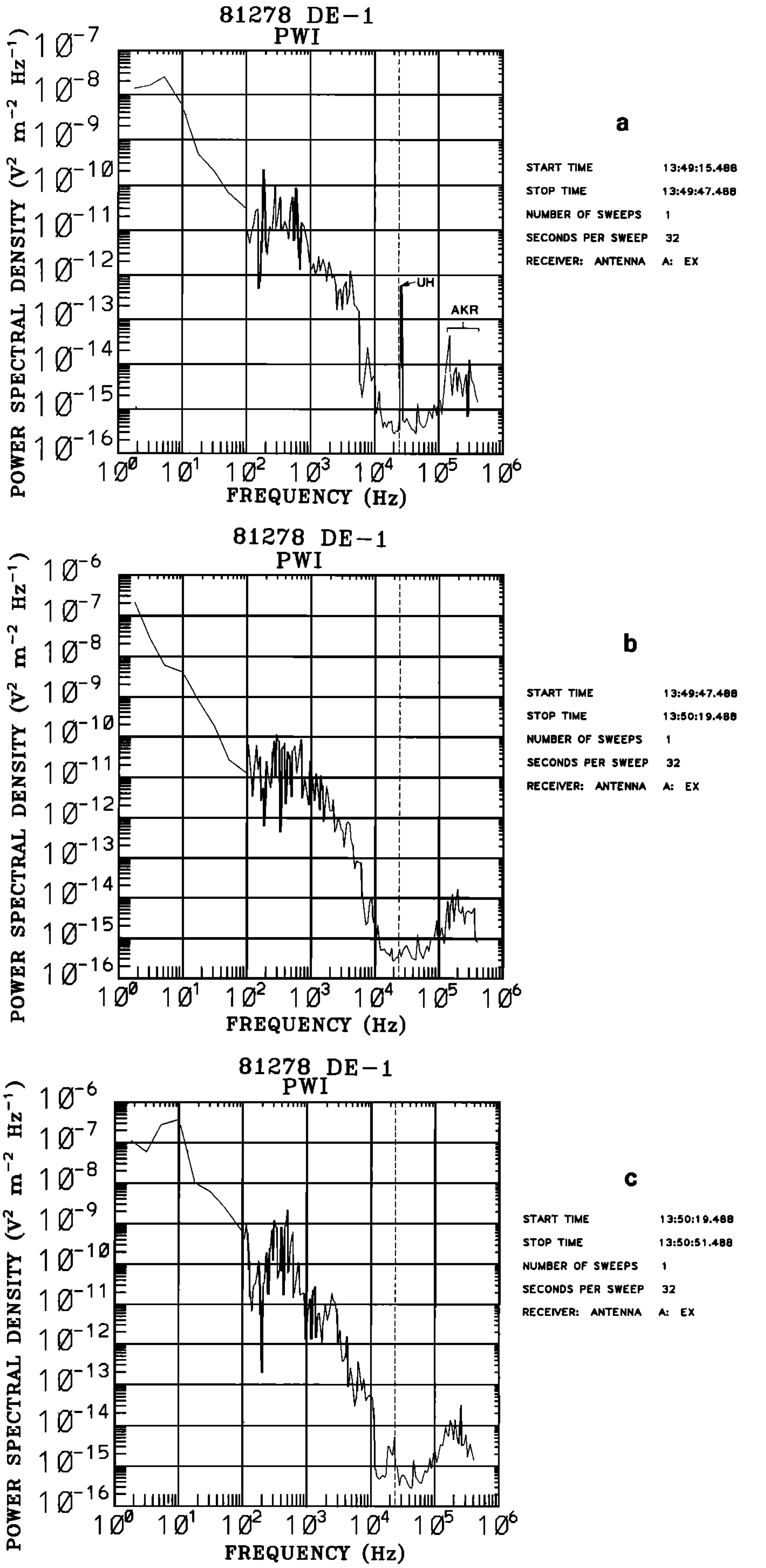


Fig. 6. A series of PSD plots obtained for times near the data shown in Figure 5. (*a*) A relatively strong peak near the gyrofrequency. (*b*) Almost no emission at the same frequency. (*c*) Data obtained simultaneously with the electron conics and a rather broad and low-intensity peak near the gyrofrequency.

cones. A plot of the PSD of the PWI electric field obtained during a time period including that of the contour is shown in Figure 8. There is emission of large intensity near the gyrofrequency ($f_{ce} \sim 55$ kHz) which we interpret as upper hybrid emission. For this pass a relatively high plasma density of about 12.5 cm^{-3} was determined from the plasma data. This yields $f_p \sim 32$ kHz, and $f_{UH} \sim 64$ kHz. The estimated electric field strength is about 2 mV/m.

Summary of DE 1 Observations

Upper hybrid emissions are present within 32 s of each occurrence of electron conical distributions shown for the HAPI data. Sometimes the correlation in time is not exact (such as the pass for day 81/278) and can differ by an amount less than or equal to the PWI sweep time of 32 s.

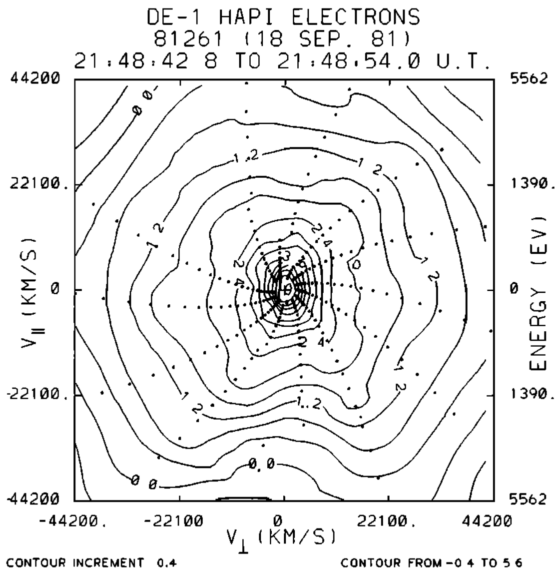


Fig. 7. Contours of the electron distribution function obtained over a two-spin period of the DE 1 satellite for the nightside auroral region pass of day 261 of 1981.

As pointed out above this may be explained due to the extremely short growth times of the waves, typically ≪ 1 s, relative to instrument integration times which are on the order of seconds. It is possible that when conics are observed, the heating due to upper hybrid waves has already occurred and the waves have already been damped. We may also explain the sometimes less-than-perfect correlation of upper hybrid waves with electron conical distributions by frequency-scan aliasing. The actual frequency of the narrow-banded upper hybrid emission is only sampled once within the 32-s sampling period. The sampling times of both the HAPI and PWI instruments make simultaneous observations of upper hybrid waves and conics unlikely.

The HAPI does not observe electron conics at pitch angles near 90°. As we noted above, however, this does not necessarily mean that DE 1 was not in the generation region. Because the electron plasma frequency is much smaller than the electron cyclotron frequency in the proposed polar cap source region, the real frequency of upper hybrid waves is very close to the electron cyclotron frequency. The instability occurs only for propagation near 90° with respect to the magnetic field, as required by the gyroresonant condition, and the wave becomes stable when the wave vector is a few degrees away from perpendicular propagation [see *Wong et al.*, 1988, Figure 1]. Energy diffusion and pitch angle scattering, however, lead to oblique heating. This is indicated by the calculations of the velocity and pitch angle diffusion coefficients which peak at oblique angles even though the wave normal angle is near 90° [see *Wong et al.*, 1988, Figures 2*a* and 2*b*]. In addition, computer simulations [cf. *Roth et al.*, 1990; *Lin et al.*, 1990] have subsequently verified that the diffusion coefficient resulting from resonant wave-particle interaction with upper hybrid turbulence is a function of both pitch angle and energy producing oblique heating of the electrons. In each of these studies plasma parameters typical of the mid-altitude auroral region (DE 1 altitudes) were assumed. In particular, the simulations show that the electron conics are not formed at pitch an-

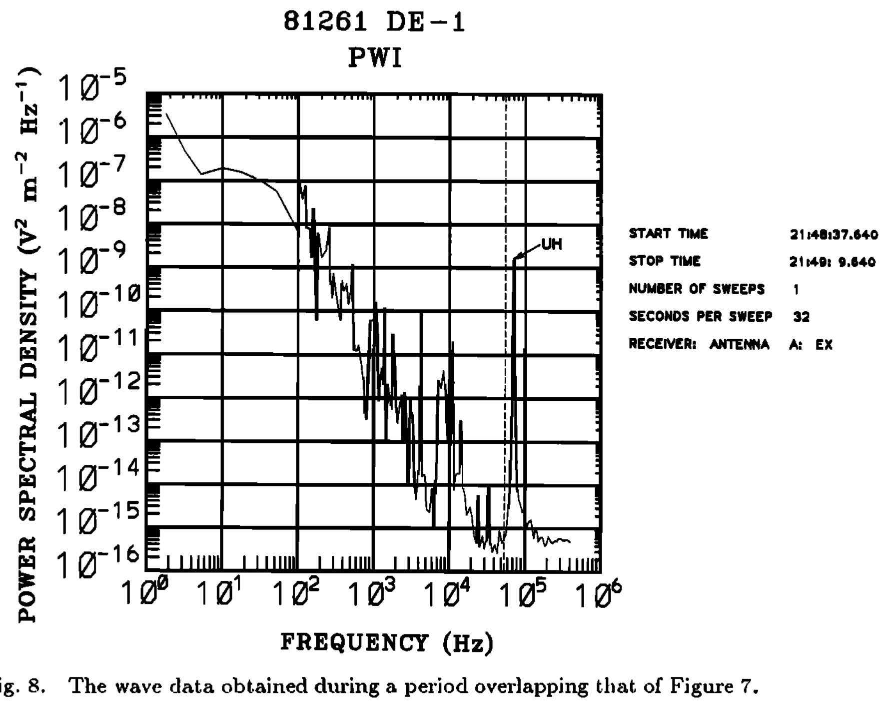
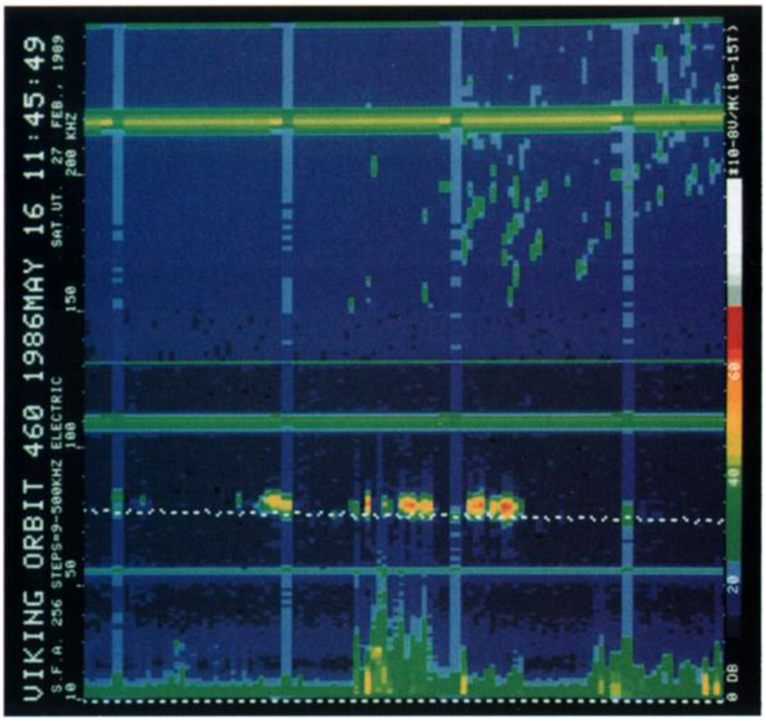
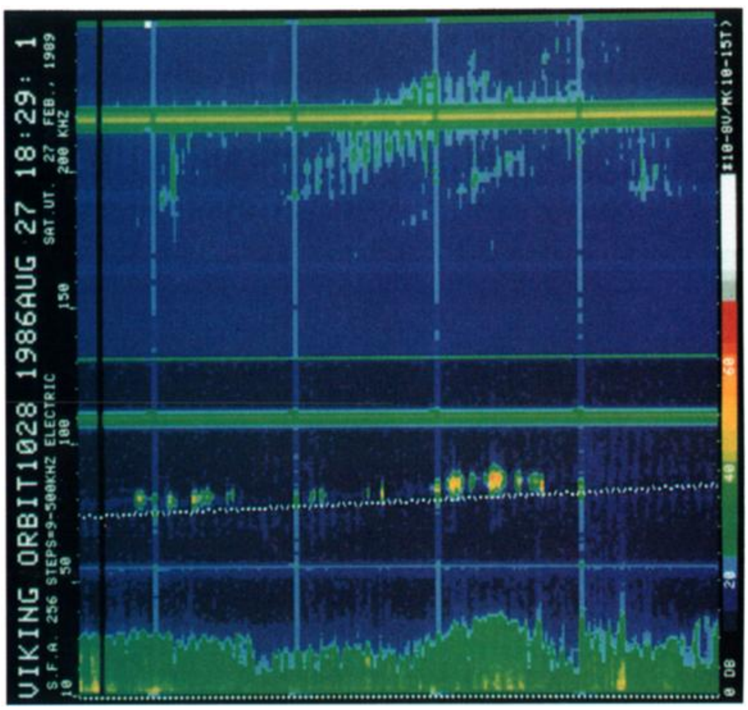


Fig. 8. The wave data obtained during a period overlapping that of Figure 7.



MLT 17.04
ILAT 73.38°
ALT(KM) 11500

Plate 2. Frequency-versus-time spectrogram with electric field intensity color-coded. The data were obtained from the Viking V-4H experiment and show distinct, intense, narrow-banded emission just above the gyrofrequency (indicated by the white dotted line). The blue vertical stripes are sounders spaced about 240 s apart. The orbit information at the beginning of the plot are indicated. This is a nightside pass and the start time of the plot is 1145:49 UT on day 136 of 1986.



ILAT 83.0
MLT 6.0
ALT(KM) 11500

Plate 3. This is a spectrogram of the Viking electric field data in the same format as Plate 2. The data of this figure are for a dayside pass and the start time of the plot is 1829:01 UT on day 239 of 1986. Again, intense emission just above the gyrofrequency are seen.

gles of 90°, but rather near 150°, just as observed by HAPI. Thus, while the source region of electron conics may extend over a large range of altitudes, it is possible that DE 1 was in a source region during the observations.

UPPER HYBRID WAVES OBSERVED BY THE VIKING SATELLITE

In addition to the DE 1 data, we have searched the Viking wave data for the presence of intense upper hybrid waves. In Plates 2 and 3 we show two examples of such waves that may have the potential of generating electron conics. These waves were observed in both the morning and afternoon sectors at a somewhat lower altitude than DE 1. The format for both figures is frequency versus time with wave intensity color-coded. The starting MLT, invariant latitude and altitude are listed. The time between the sounders (the vertical blue lines) is approximately 240 s. The white dotted-line indicates the electron gyrofrequency. So the intense emissions (yellow and red) just above this dotted line in both figures are indicative of upper hybrid emissions. The wave amplitude is typically 10^{-5} $V/(m\sqrt{Hz})$. Taking a bandwidth of 2 kHz (two SFA channels), we obtain about 0.3 mV/m.

We have analyzed the particle data available from the Viking V-3 experiment, but no electron conics were observed for either pass. As indicated above, this may only indicate that the waves have not yet heated the electron population. The presence of intense upper hybrid emissions at mid-altitudes have only recently been reported [e.g., *Farrell et al.*, 1990], and the Viking data must be more carefully analyzed to determine the presence of more intense upper hybrid emissions and the association with electron conical distributions.

SUMMARY AND DISCUSSION

In this paper we have shown the presence of intense upper hybrid waves in the midaltitude polar magnetosphere and demonstrated that these waves are sometimes associated with electron conical distributions. Confirmation of the pressure of intense upper hybrid waves in the mid-altitude polar magnetosphere is important in light of the lack of similar observations at lower altitudes of the AUREOL/ARCAD 3 satellite as reported by *Beghin et al.* [1989]. These observations suggest that upper hybrid waves may at least sometimes be a source of oblique heating of electrons and electron conical distributions. This analysis does not preclude the generation of electron conical distributions resulting from parallel heating processes as suggested by *Roth et al.* [1990] and *Temerin and Cravens*, [1990] and alluded to by *Lundin et al.* [1987]. Nor do the observations presented here explain the electron conical distributions observed by *Lundin et al.* [1987] that were not associated with loss cones or ring distributions. The efficiency of the mechanism of perpendicular heating by upper hybrid waves is demonstrated by simulations by *Roth et al.* [1990] and *Lin et al.* [1990]. The observations presented in this paper are consistent with the production of at least some electron conical distributions by oblique heating of the electrons due to upper hybrid waves. Examination of the wave data to establish the role of parallel heating remains to be performed.

Acknowledgments. We would like to thank Tony Sawka for drafting the figures and Leah Roberson for clerical work. We are especially grateful to Mats Andre for providing Viking particle data and for many useful comments and discussions. This work was supported at SwRI by NASA grants NAS5-28711 and NAG5-1552.

The Editor thanks J. F. Fennell and M. A. Temerin for their assistance in evaluating this paper.

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A. Bahnsen, Danish Space Research Institute, Lundtoflevej 7, Lyngby, DK-2800, Denmark.

D. A. Gurnett, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242.

C. S. Lin, J. D. Menietti, and H. K. Wong, Southwest Research Institute, 6220 Culebra, San Antonio, TX 78228.

(Received April 1, 1991;
revised September 3, 1991;
accepted September 5, 1991.)