JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. A1, PAGES 75–83, JANUARY 1, 1984

Chorus-Related Electrostatic Bursts at Jupiter and Saturn

L. A. REINLEITNER,[1] W. S. KURTH, AND D. A. GURNETT

Department of Physics and Astronomy, The University of Iowa

Analyses of the wide band plasma wave data obtained by Voyager 1 and 2 at Jupiter and Saturn have revealed electrostatic bursts similar to those recently discovered at earth in association with whistler mode chorus. In all three magnetospheres the bursts are characterized by sporadic emissions near or slightly below the electron plasma frequency with bandwidths ranging from 10% to more than 50% of the center frequency. The events found at Jupiter occur in the middle magnetosphere during both the dayside as well as the early morning passes. At Saturn the bursts occurred in the outer regions of the magnetosphere during the dayside pass. In each of the events analyzed, evidence exists for modulation of the electrostatic bursts by a low-frequency wave, presumably chorus. One of the observations gained at Jupiter includes the detection of a low-frequency band at the proper frequency for chorus. Detailed waveform analysis confirms that this band does, indeed, modulate the electrostatic bursts. On the basis of the present understanding of the terrestrial observations, it is believed that the electrostatic bursts are generated by an electron beam trapped in Landau resonance with the chorus.

1. INTRODUCTION

Reinleitner et al. [1982] have described bursts of electrostatic noise that occur in the terrestrial magnetosphere in association with whistler mode emissions. On the basis of further analysis of these emissions by *Reinleitner et al.* [1983] and *Gurnett and Reinleitner* [1983], it is now believed that the electrostatic bursts are produced by a "beam" of electrons trapped in Landau resonance with the chorus. These observations provide the first clear evidence of electron trapping and acceleration by Landau resonance interactions with whistler mode waves. Since such interactions can possibly cause the precipitation and loss of trapped radiation belt particles, it is of considerable general interest to determine if similar Landau resonance interactions are occurring in other planetary magnetospheres. In this paper we show observations from the magnetospheres of both Jupiter and Saturn of similar emissions obtained by the Voyager 1 and 2 plasma wave instruments.

The terrestrial electrostatic emissions have been well characterized by *Reinleitner et al.* [1982, 1983]. The bursts often occur in one-to-one correspondence with discrete chorus emissions with a hooklike appearance. In such cases the electrostatic emissions are amplitude modulated at the chorus frequency. The electrostatic waves have typical amplitudes of 50 μV m^{-1} and are similar to Langmuir waves in that the frequency is near the electron plasma frequency f_p and the wave electric field is aligned nearly parallel to the geomagnetic field. However, the bursts are downshifted to a frequency somewhat below the electron plasma frequency, sometimes by as much as 50%, and have a bandwidth broader than that of the usual Langmuir waves. The chorus has typical electric and magnetic field strengths of 300 μV m^{-1} and 40 pT, respectively.

A theoretical model proposed to explain these observations [*Reinleitner et al.*, 1983] is based on the fact that for oblique propagation the chorus emissions have an electric field component parallel to the magnetic field $\mathbf{B}_0$. This electric field produces an effective potential well for particles moving along the magnetic field. Electrons moving at nearly the chorus phase velocity can then be trapped in the potential well and accelerated by changes in the phase velocity, such as those due to inhomogeneities in the plasma. *Gurnett and Reinleitner* [1983] also discuss another acceleration mechanism called dispersive acceleration, which occurs when trapped particles are carried through the chorus wave packet. In either case, electrons are transported to higher velocities and appear as a bump in the distribution function. These electrons are spatially bunched near the minimum of the potential well, and each bunch excites a burst of electrostatic noise via a two-stream instability.

Because the observed electrostatic wave frequency is often considerably below f_p, *Reinleitner et al.* [1983] suggest that the resistive-medium instability [*Briggs*, 1964] may be responsible for the electrostatic instability. The resistive-medium instability occurs when the beam velocity v_b is comparable to or less than the electron thermal velocity v_{th}. One of the desirable characteristics of the resistive-medium instability is that the frequency of maximum growth rate is shifted well below the electron plasma frequency, which agrees with the observations. The basic instability mechanism has been explored further by *Grabbe* [1983], who considered both the resistive-medium ($v_b < v_{th}$) and beam-plasma ($v_b > v_{th}$) regimes. Grabbe concluded that the electrostatic instability could be operating in either regime, depending on the parameters of the medium. Grabbe also considered the possible effects of finite beam temperatures.

2. OBSERVATIONS AT JUPITER

Figure 1 shows examples of electrostatic bursts observed in the Jovian magnetosphere. The data are presented in the form of a frequency-time spectrogram in which the amplitudes of the waves are plotted as a function of frequency (ordinate) and time (abscissa). The most intense waves appear black in this representation. These data are obtained from the wide band waveform channel of the Voyager 1 plasma wave receiver [*Scarf and Gurnett*, 1977]. The emissions in the range of 5 to 10 kHz have several of the characteristics of the terrestrial chorus-induced electrostatic bursts. While there is no magnetic sensor on Voyager to provide confirmation that these bursts are electrostatic, we use their sporadic nature as circumstantial evidence that they are not freely propagating electromagnetic emissions. *Kurth et al.* [1983] provide a more detailed justification for the electrostatic identification of similar bursts at Saturn.

The two most obvious properties of the electrostatic bursts are their impulsive nature and relatively large bandwidths.

---

[1] Now at Max-Planck-Institut fur Aeronomie.

Paper number 3A1553.
0148-0227/84/003A-1553$05.00

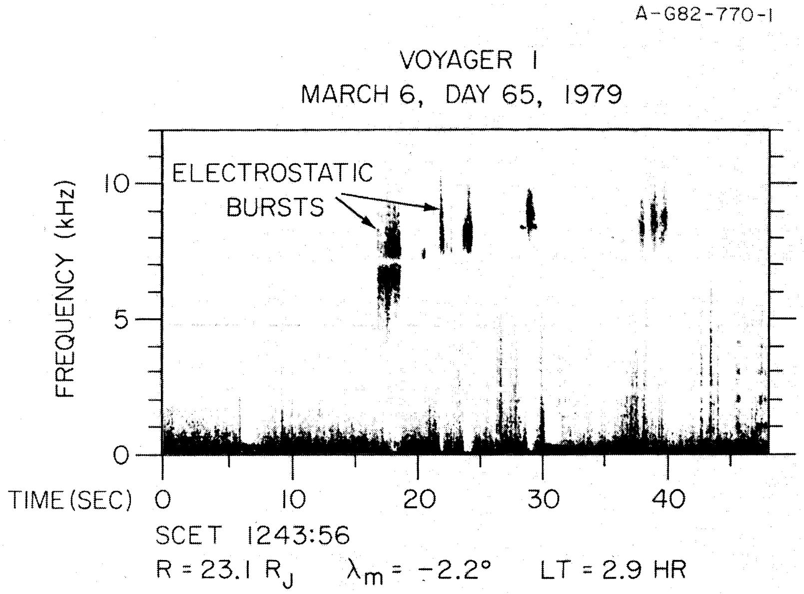

Fig. 1. A frequency-time spectrogram showing electrostatic bursts in the Jovian nightside middle magnetosphere. The relationship between broader bandwidth and lower frequency apparent here is predicted by theory. Note that the gap in the first burst at 7.2 kHz is an instrumental effect and not real.

The bursts turn on and off quite abruptly and have durations ranging from 0.1 s to more than a second. The bandwidth is variable but is a substantial fraction of the center frequency. Figure 2 shows average spectra from two of the bursts shown in Figure 1 in order to show more clearly the spectral character of the emissions. The lower spectrum in Figure 2 is an average over the first burst at about 18 s into the frame in Figure 1. The full width at half maximum (FWHM) bandwidth is about 2.6 kHz, so that $\Delta f/f$ is about 30%. The gap in the emission at 7.2 kHz is due to a notch filter in the receiver which is designed to filter out the third harmonic of the power supply frequency and, therefore, is not real. The total integrated amplitude of this burst is $\sim 50\ \mu\mathrm{V\ m^{-1}}$.

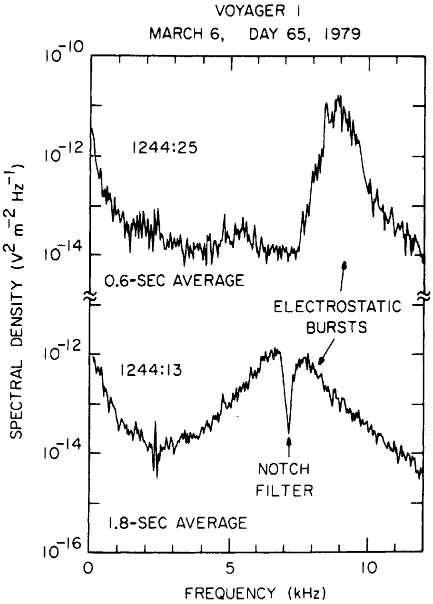

Fig. 2. Detailed spectra of two of the bursts shown in Figure 1 showing the relative frequency spread of the two bursts which are centered at significantly different frequencies.

The spectrum in the top panel of Figure 2 is from ~ 29 s into the frame shown in Figure 1. This burst is centered at a higher frequency (9 kHz) and has FWHM bandwidth of only about 1 kHz so that $\Delta f/f \approx 11\%$. The integrated amplitude of this burst is about $100\ \mu\mathrm{V\ m^{-1}}$. It is possible that the variations in the burst frequencies are simply reflecting local variations in the plasma density; however, it is also possible that the variations are being caused by changes in the beam velocity or electron thermal velocity, as would be predicted by the theory outlined in the work of *Reinleitner et al.* [1983]. The theory predicts that the both bandwidth and the downshift in frequency depend on the ratio of the beam velocity v_b to the background thermal velocity v_{th}.

The electron density as measured by the plasma probe at 1243 spacecraft event time (SCET) is not inconsistent with a plasma frequency near 10 kHz (E. C. Sittler, Jr., personal communiation, 1983), and there is considerable variability on time scales of a few minutes. However, the electron density is not available at high enough time resolution to resolve the issue, and one might assume that f_p remains nearly constant over the $\sim$20-s interval covered by the burst activity in Figure 1. One can then see that the burst at 1244:13 SCET is both broader in bandwidth and centered at a lower frequency (and presumably downshifted further with respect to f_p) than the one at 1244:25. *Reinleitner et al.* [1983] show that the low-frequency, broader bursts are generated in cases of smaller v_b/v_{th} than the higher-frequency, narrower bursts. Hence the variations in frequency and bandwidth shown in Figures 1 and 2 are consistent with the theory, given that f_p remains constant over the interval of interest.

The bursts shown in Figure 1 are located on the nightside at a radial distance of 23.1 R_J, in the middle magnetosphere. Figure 3 shows another example of burst activity that occurs over an extended region of the dayside middle magnetosphere, lasting for several hours. Plotted are amplitudes from the 16-

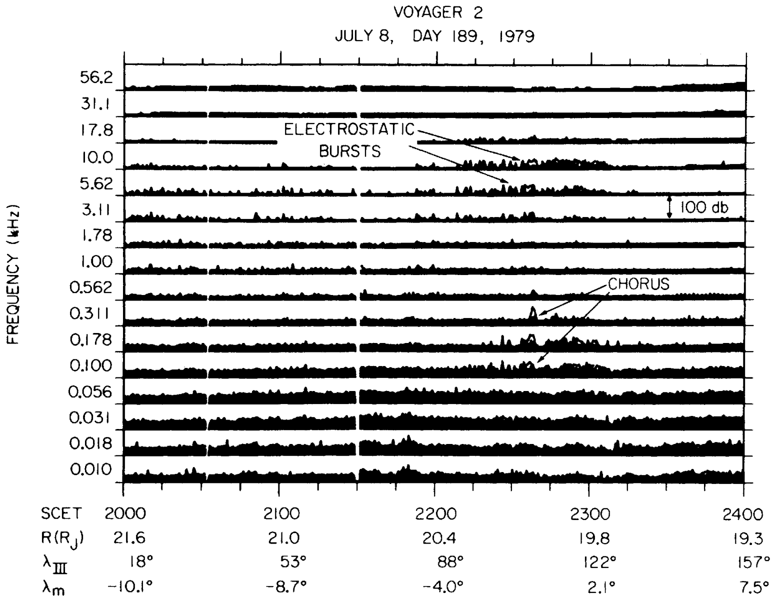

Fig. 3. Spectrum analyzer data showing a concentration of electrostatic bursts near the magnetic equator ($\lambda_m = 0°$) and chorus emissions centered at the equator. These data were obtained in the dayside middle magnetosphere of Jupiter.

channel spectrum analyzer portion of the plasma wave receiver as a function of time. The height of the solid black area for each channel is proportional to the logarithm of the electric field strength averaged over 24-s intervals with the total dynamic range approximately 100 dB below 100 mV m^{-1}. Peak electric field strengths obtained over each 24-s interval are plotted and connected by a solid line. The electrostatic bursts are most evident in the peak electric field strengths, as in the 10-kHz channel at 2230 SCET.

Bursty emissions can be seen primarily in the 5.62- and 10.0-kHz channels in Figure 3 between about 2200 and 2310 SCET. For a large portion of this interval, enhanced wave amplitudes are also visible in the range of a few hundred hertz. These low-frequency emissions are believed to be chorus. The identification of the low-frequency emission as chorus is based largely on the frequency, since f_g over this interval is ~ 1 kHz and chorus, if present, would probably lie near or slightly below $f_g/2$. Further reasons for the identification as chorus are discussed below. It is interesting that the electrostatic bursts are centered near the magnetic equator and that the most intense burst of chorus is located almost exactly on the equator.

A detailed spectrogram of some of the bursts shown in Figure 3 is given in the left-hand panel of Figure 4. In this case the bursts occur at a nearly constant frequency with $\Delta f/f \lesssim 10\%$. However, other bursts from this general time interval show much broader bandwidths and great variability in the center frequency. The interesting aspect of this example is the simultaneous occurrence of a band of noise at lower frequencies which is detailed in the right-hand panel of the figure.

The plasma frequency during this time is near 10 kHz, as determined by the Voyager plasma instrument (E. C. Sittler, Jr., personal communication, 1983), which is close to the frequency of the electrostatic emission. The magnetic field is $|B_0| \sim 39$ nT (R. P. Lepping, personal communication, 1982) so that the electron gyrofrequency f_g ($= 28|B_0|$ in hertz) is about 1.1 kHz. The low-frequency band lies below about 400 Hz and is therefore most likely a whistler mode emission. In fact, since chorus is typically found near $f_g/3$, it is likely this

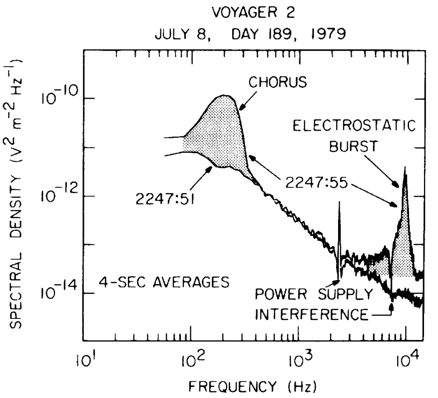

Fig. 5. Two 4-s average spectra taken from Figure 4 at a time when neither chorus or electrostatic bursts are observed (2247:51 SCET) and when both are present (2247:55 SCET). These observations suggest an interaction between the two modes. The gyrofrequency at this time is ~ 1.1 kHz.

band is chorus, even though discrete chorus emission cannot be seen in the band.

The electrostatic bursts shown by *Reinleitner et al.* [1982, 1983] were often associated with homogeneous bands of chorus similar to the band in the right-hand panel of Figure 4. Close inspection of the chorus and electrostatic bursts in Figure 4 reveals a good correlation between the occurrence of the two emissions even though this correspondence is not always one to one. The electrostatic waves are always accompanied by the chorus, but the converse is not true. Figure 5 details this correspondence by showing two consecutive 4-s average spectra taken from Figure 4 in which the chorus and electrostatic bursts are clearly evident in one but neither is visible in the other. The shaded regions highlight the differences between the two spectra. The integrated electric field strengths of the bursts and chorus band are ~ 60 and ~ 140 $\mu V\ m^{-1}$, respectively. These intensities are both very similar to terrestrial amplitudes as reported by *Reinleitner et al.* [1983].

We should point out that the automatic gain control (AGC) circuit in the receiver is responsible for two possibly confusing effects in Figures 4 and 5. In Figure 4 the chorus band occasionally disappears and the AGC goes to a higher gain state (for example, between 30 and 37 s into the frame). Hence the low-frequency background noise at these times appears to increase in the spectrogram at frequencies up to 1 kHz or so, even though it is weaker than the chorus band. In Figure 5 the noise levels of the two spectra do not match at higher frequencies (near 12 kHz) because the gain is set higher for the spectrum taken at 2247:51, and therefore the receiver threshold is set lower.

In neither of the preceding examples were we able to show accurately the relationship between the burst frequency and f_p because of inaccuracies in the measured electron density. Hence we show in Figures 6 and 7 examples of electrostatic bursts that occur when accurate measurements of f_p are provided by cutoffs and resonances in the plasma wave spectrum. In Figure 6 the diffuse emission with a sharp lower-frequency cutoff just above 2 kHz is trapped continuum radiation. The cutoff has been shown to be very close to f_p by *Gurnett and Shaw* [1973] and *Shaw and Gurnett* [1980] for the terrestrial continuum radiation. Sporadic electrostatic bursts are visible at numerous times in this figure, all well below f_p. The burst occurring early in the frame below 1 kHz is broadband electrostatic noise and is distinguishable from the electrostatic bursts occurring later by a spectrum which peaks at very low frequencies.

The spectrogram in Figure 7 shows electrostatic bursts with very large bandwidths during a time when a band near the upper hybrid resonance (UHR) frequency $f_{UHR} = (f_p^2 + f_g^2)^{1/2}$ is observed. Since the magnetic field strength is only 20 nT [*Lepping et al.*, 1981], f_g is small (560 Hz) and $f_p \approx f_{UHR}$. Notice that the center frequency of the bursts is well below f_p. This example is also interesting in that there is good evidence for discrete chorus emissions at about $f_g/2$. As for the case shown in Figure 4, there is a good correlation between the occurrence of electrostatic bursts and chorus during this time interval.

In order to investigate further the relationship between the electrostatic bursts and chorus emissions illustrated in Figure 4, we have performed a waveform analysis similar to that used by *Reinleitner et al.* [1982]. In this analysis the waveform data were filtered at the burst frequency as well as at the chorus frequency and displayed in the time domain on a common scale. Figure 8 details the results of this analysis. In each panel of the figure, the two traces correspond to the waveform of the

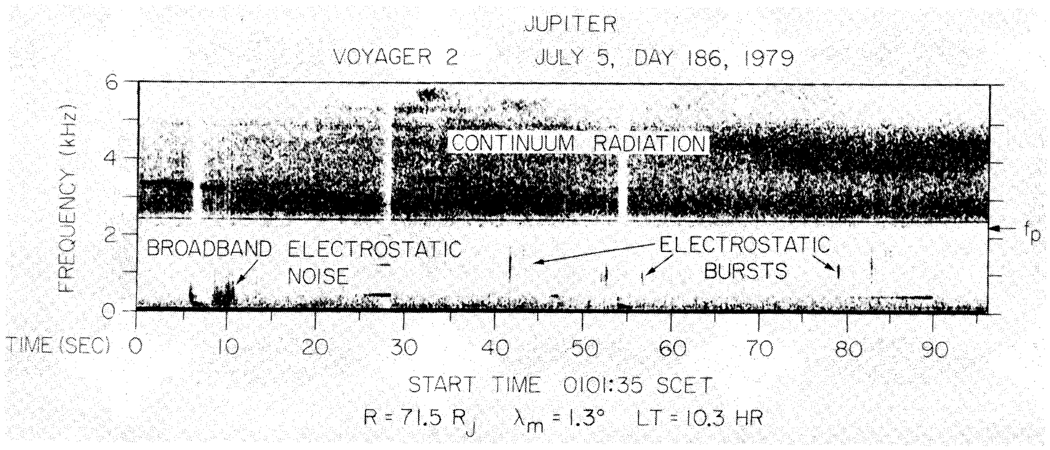

Fig. 6. A frequency-time spectrogram showing the occurrence of electrostatic bursts well below f_p as determined by the low-frequency cutoff of continuum radiation. Also note the distinction between the bursts and the broadband electrostatic noise occurring early in the frame.

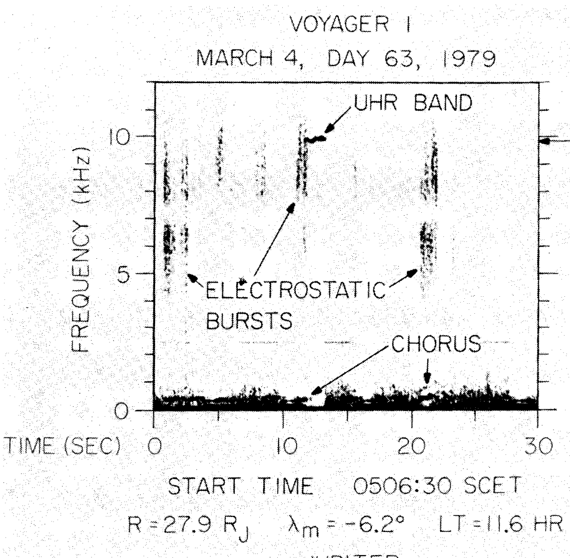

Fig. 7. An example of very broadband electrostatic bursts occurring at a time when a band at the upper hybrid resonance (UHR) frequency is observed. At this time, $f_p \approx f_{\mathrm{UHR}}$ and the center frequencies of the bursts are well below the UHR band. Note the correlation between the occurrence of the electrostatic bursts and discrete chorus emissions.

electrostatic bursts (upper trace) and the chorus wave (lower trace). Because different band-pass filters were used for each channel a small, but constant, phase shift occurs between the two signals. However, even though the absolute phase relationship between the two signals is not preserved, the nearly one-to-one correspondence between the electrostatic bursts and the chorus can be clearly seen.

Figure 8*a* shows a brief interval of burst activity taken from about 12 s into the frame in Figure 4 and shows a very good correspondence between the burst envelope and the waveform of the low-frequency chorus emission. Keep in mind that the interval covered is only a small portion of the burst. According to the theory of *Reinleitner et al.* [1983] the modulation is caused by the spatial bunching of electrons trapped in the potential well of the chorus wave.

Figures 8*b* and 8*c* show the waveform analysis for two other intervals from Figure 4 at about 30 s into the frame. The time scale is more compressed for these two panels but still shows a relatively good correlation between peaks in the burst envelope and the chorus wave. In these two cases, though, the effects of a broad, nonmonochromatic chorus emission are seen in the rather complex chorus waveform. *Reinleitner et al.* [1982] found the modulation effect to be less pronounced at the earth for broad bands of chorus such as in Figure 4 compared with bursts associated with discrete hooks which are nearly monochromatic at a given instant in time.

The bursts shown in Figure 4 show substantial evidence of modulation by the simultaneously observed chorus band and are very similar to the electrostatic bursts studied by *Reinleitner et al.* [1982, 1983] at the earth. The first cases presented in Figures 1 and 2 show considerable wave amplitudes below a few hundred hertz which would be consistent with chorus, since f_g is in the range of 300 to 800 Hz during this interval (R. L. Lepping, personal communication, 1982). However, we cannot be absolutely certain that the low-frequency noise is chorus, because there is nothing to differentiate the spectrum at low frequencies from other types of emissions or interference in the same frequency range.

If, however, there is chorus present but "hidden" by other emissions, it would still be possible to observe the modulation effects even though the chorus itself is not observable. In fact, close inspection of the dynamic spectrum in Figure 1 reveals some suggestion of harmonically related structures with a spacing of ~200 Hz, especially in the first burst about 18 s into the frame. Figure 9 shows the electrostatic burst envelope for two periods during the frame shown in Figure 1. Figure 9*a* is from the burst 24 s into the frame, and Figure 9*b* is from the burst 29 s into the frame. Both waveforms show modulation effects, although they are very complex. In both panels there is

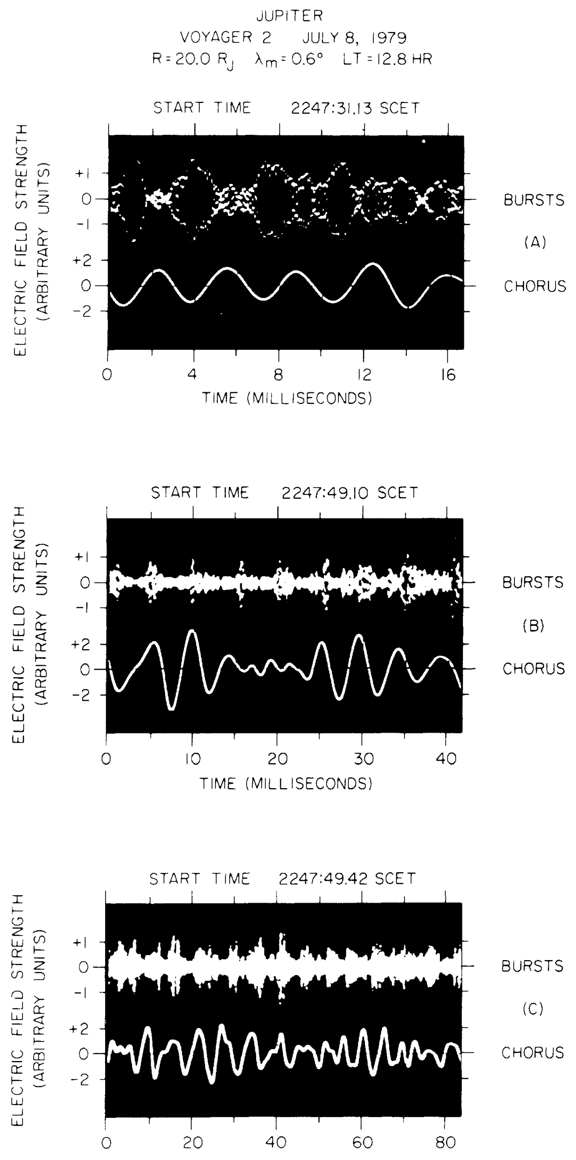

Fig. 8. The results of waveform analyses performed on the observations presented in Figure 4 showing the modulation of the high-frequency electrostatic bursts (upper waveforms) by the low-frequency chorus emission (lower waveforms). All three examples show relatively good correspondence between the burst modulation and the phase of the chorus wave. Note that the absolute phase relation between the two traces has not been preserved in the analysis.

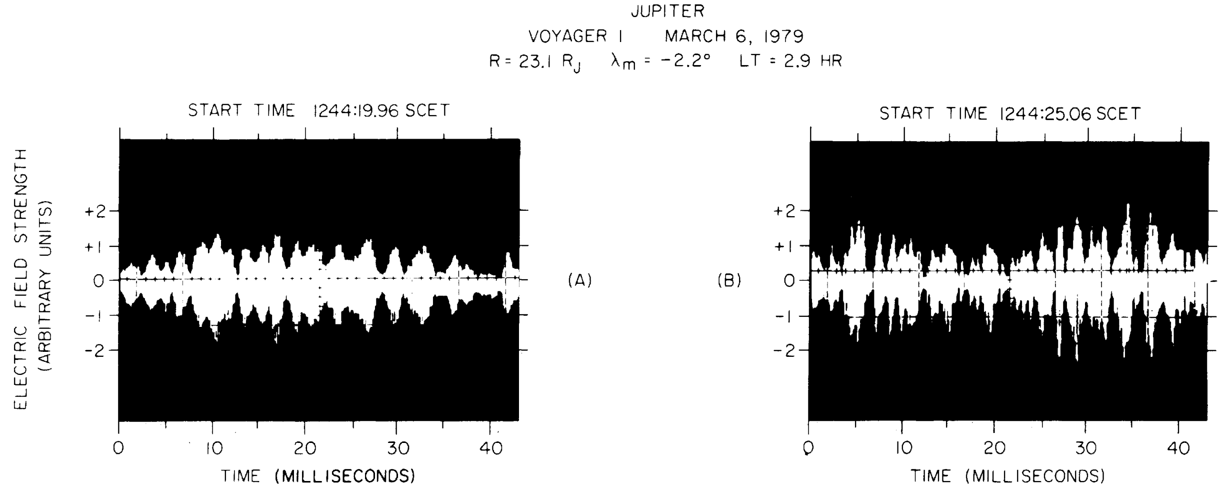

Fig. 9. The waveform envelope for portions of two of the bursts shown in Figure 1. In these examples the chorus wave is not shown, since it cannot be clearly distinguished from other low-frequency noise or interference occurring at the time. Still, evidence of a modulation effect can be seen at frequencies in a range which is reasonable for chorus.

evidence of a fairly low frequency modulation (~200 Hz), but there are also higher-frequency effects. The 200-Hz modulation pattern might reasonably be attributed to some chorus interaction, but the explanation of the higher-frequency effects is unknown at present. We suggest that the waveform analyses presented in Figure 9 are supportive of our interpretation as a chorus interaction but do not provide conclusive evidence of a chorus association.

Electrostatic bursts with features similar to those shown in the examples above are relatively common in the Jovian magnetosphere. To gauge just how common they are, we surveyed all of the wide band frames processed thus far within the magnetosphere (a total of ~1000) for evidence of the bursts. We looked for sporadic bursts occurring near but perhaps somewhat below f_p (based on the continuum radiation cutoff and UHR bands when present). In order not to count possible examples of broadband electrostatic noise which peak below 100 Hz, we accepted only those events which clearly peaked at frequencies above about 1 kHz.

The results of the survey are summarized in Figure 10, in which the trajectories of Voyager 1 and 2 are plotted. Circles are positioned on each trajectory representing periods during which bursts were observable which met the above criteria. Most of the circles represent periods when several bursts were detected, and in all about 120 48-s frames were found which showed evidence of the bursts.

While it is clear that the dayside outer magnetosphere seems to be a favored location for the bursts, we caution the reader not to draw unwarranted conclusions. First, during the passes through the inner magnetosphere, f_p is above the 12-kHz upper cutoff of the waveform receiver; hence the absence of events inside ~20 R_J may be due to limitations of the instrument. Second, the frames used in the survey are not located uniformly along the trajectory but only where the

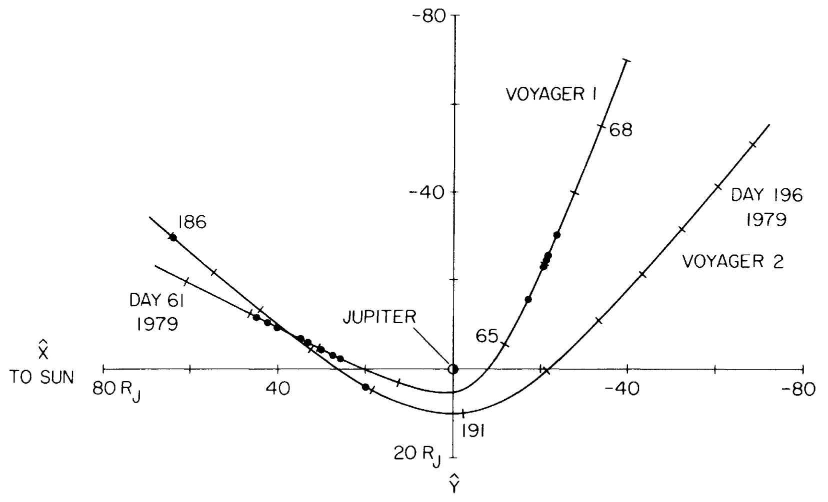

Fig. 10. Circles representing periods when electrostatic bursts were observed are superimposed on the trajectories of Voyager 1 and 2 projected onto Jupiter's orbital plane. Most of the circles represent an extended period during which several bursts were detected. Note that the dayside is a favored location for the electrostatic bursts, although the uneven spacing of available wide band frames used for the survey makes the validity of such a conclusion suspect.

high-rate telemetry link was available and not used for imaging [*Scarf et al.*, 1981]. Further, the frames processed to date were chosen for their possible application to a variety of different avenues of research and certainly do not qualify as a random selection. For example, more frames have been processed on the two inbound legs than on the outbound passes, so the apparent day/night asymmetry may not be real.

Still, the survey does show that the bursts, if correctly identified, occur frequently in the outer magnetosphere, and it appears the events are grouped into fairly well defined intervals of occurrence and not randomly distributed. This result, of course, is subject to the above precautionary statements. Nevertheless, there are extended regions for which wide band frames have been processed but which show no evidence for the electrostatic bursts. It is also clear that the episodes of occurrence on the outbound (nightside) legs show significantly fewer bursts than do many of the dayside episodes.

3. OBSERVATIONS AT SATURN

The first evidence of chorus-induced electrostatic waves at Saturn was given by *Kurth et al.* [1983]. In this section we shall review the Saturn data and show the results of waveform analyses of the form given above for the Jovian observations. We note here that the amount of wide band waveform data available is substantially less at Saturn (by ~2 orders of magnitude) than at Jupiter [*Scarf et al.*, 1983]; hence the amount of data available to search for electrostatic bursts is severely restricted.

The bottom panel of Figure 11 [from *Kurth et al.*, 1983] is a frequency-time spectrogram that shows sporadic bursts at about 8 kHz having dynamic spectral characteristics similar to those from Jupiter shown in Figures 1 and 4. The bandwidths of these Saturnian emissions are somewhat less than the Jovian examples, but the burst durations are quite similar. In the top panel of Figure 11 the response of several of the Voyager 1 plasma wave spectrum analyzer channels is plotted. The spectrum analyzer observations have much lower spectral and temporal resolution than the wide band waveform display but show an extended region in the dayside outer magnetosphere of Saturn near $R = 16\ R_S$ having the burst activity. Typical electric field strengths for these emissions is $\sim 10\ \mu\text{V m}^{-1}$.

The total charge density determined by the plasma instrument's ion measurements is not inconsistent with a plasma frequency of about 8 kHz (A. J. Lazarus, personal communication, 1983) as implied by the frequency of the bursts in the bottom panel of Figure 11. Further, a time profile of f_p based on the electron analysis shows variations that track the burst frequency in the 5.62- and 10.0-kHz channels in the top panel, even though that profile is shifted to slightly lower frequencies (E. C. Sittler, Jr., personal communication, 1983). In view of the coarse frequency spacing of the spectrum analyzer channels and a few tens of percent error typical of the plasma probe density determination, the agreement is quite reasonable and supports our identification of the burst frequency as being close to f_p.

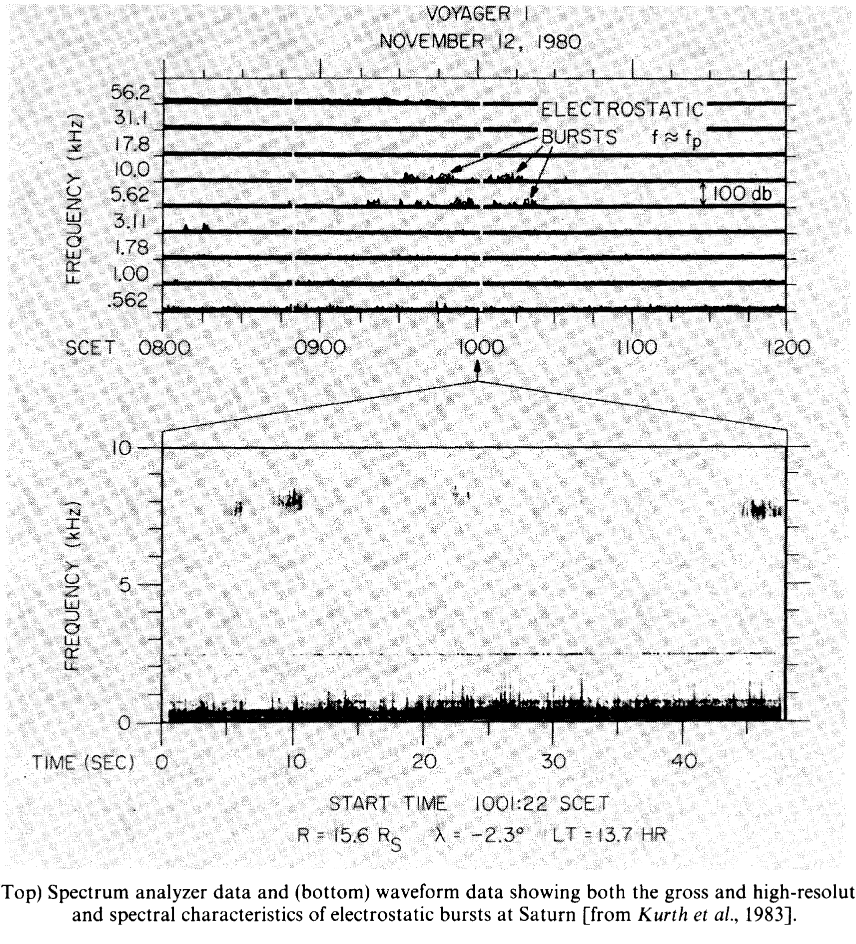

Fig. 11. (Top) Spectrum analyzer data and (bottom) waveform data showing both the gross and high-resolution dynamic and spectral characteristics of electrostatic bursts at Saturn [from *Kurth et al.*, 1983].

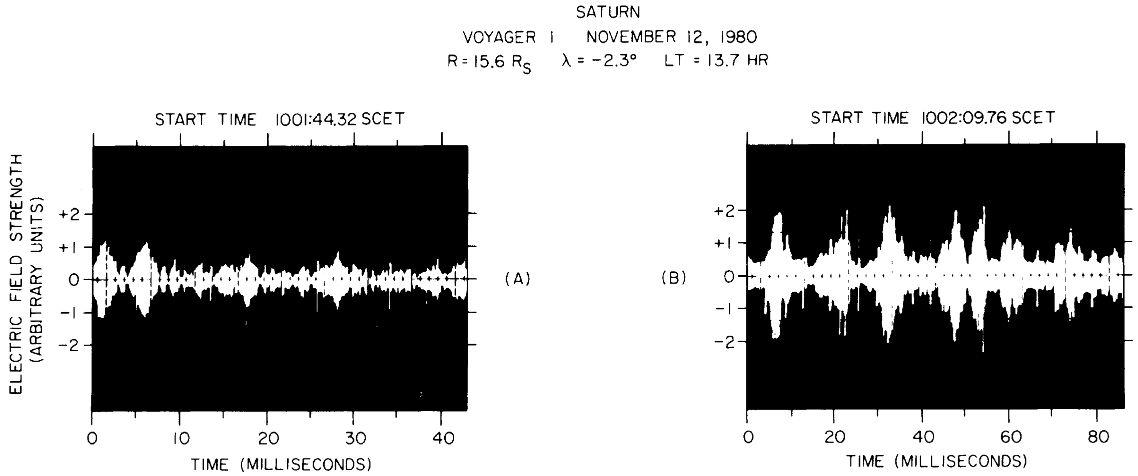

Fig. 12. Waveform analysis of two of the Saturn bursts shown in the bottom panel of Figure 11. As in Figure 9, no chorus wave can be detected because of interference from the on-board tape recorder, but a definite modulation effect can be seen, particularly in the right-hand panel.

Kurth et al. [1983] argued that the bandwidth of the Saturnian emissions was too great for either the usual Langmuir waves or electron cyclotron harmonic waves near the upper hybrid frequency. They further pointed out that some harmonic structure can be seen upon close inspection of the frequency-time spectrogram with a frequency spacing of ~100 Hz. Since the magnetic field strength is ~10 nT (R. P. Lepping, personal communication, 1982), f_g is ~280 Hz and one could interpret the harmonic structure as a modulation effect from a band of chorus at about $f_g/3$.

Unfortunately, the on-board tape recorder used to record the waveform data shown in the bottom panel of Figure 11 produces interference below about 300 Hz which completely masks any chorus emission that might be responsible for a modulation effect in the electrostatic bursts. We have therefore analyzed the burst waveforms for modulation effects in a manner similar to that used to produce Figure 9. The results are presented in Figure 12.

Figure 12*a* shows a portion of the weak burst occurring ~22 s into the frame at the bottom of Figure 11. Certainly, some modulation effects can be seen, and one can make a case, albeit weak, for periodicities of ~10 ms, especially in the weaker bursts toward the end of the interval. This would be consistent with modulation by a 100-Hz chorus emission.

The modulation is much more apparent in Figure 12*b* corresponding to the burst occurring near the end of the frequency-time spectrogram in Figure 11. The burst envelope shows very pronounced modulation at a frequency of somewhat less than 100 Hz. The modulation pattern, though, is not as regular as one might wish. However, if the chorus has a broad bandwidth and the waveform shows complexity similar to that in Figures 8*b* and 8*c*, a somewhat irregular modulation pattern might be expected.

The only other potential examples of chorus-induced electrostatic bursts were observed by Voyager 1 near 1830 SCET on day 317 of 1980 on its inbound leg on the dayside (1442 hours local time) at $R = 7\ R_S$ and at $-16°$ latitude [*Gurnett et al.*, 1981]. No waveform data exist for these bursts, however, so their identification cannot be confirmed. Other possible mode identifications consistent with the observations at 7 R_S are Langmuir waves or electrostatic bands near the upper hybrid resonance frequency.

4. Discussion and Conclusions

We have given evidence of electrostatic bursts occurring in both the Jovian and Saturnian magnetospheres that are apparently strongly influenced by waves at much lower frequencies. In two of the cases at Jupiter the lower-frequency wave is also observable and tentatively identified as chorus. The observations are consistent with the model proposed by *Reinleitner et al.* [1983] for similar terrestrial emissions in which Langmuir-like emissions are generated via a type of two-stream instability driven by electrons in Landau resonance with the chorus wave.

While some of the evidence presented is circumstantial in nature, virtually all of the observed characteristics of the terrestrial bursts have been seen in the Jovian and Saturn emissions. These include broadband sporadic emissions and harmonic structures spaced at the chorus frequency. The bursts show modulation at a frequency that would be consistent with modulation caused by a chorus wave. The events at Jupiter and Saturn occur predominantly in the dayside outer and middle magnetosphere, as is the case at the earth. In one case the theoretically predicted variations of bandwidth and downshift in frequency below f_g were observed if f_p was assumed to be constant over a short interval.

There has been no direct evidence for field-aligned electron beams accelerated via the Landau resonance interaction associated with events at either Jupiter and Saturn. On the basis of studies of the electron beams at the earth [*Reinleitner et al.*, 1983], the beam energy is typically 500 eV with a temperature as low as 10 eV corresponding to the depth of the potential well formed by the chorus wave. The plasma conditions for the terrestrial examples are similar to those at the outer planets; hence the beam characteristics should also be similar. Although 500 eV is in the correct energy range for detection by the plasma instrument on Voyager, the Voyager instrument is not configured properly to detect such a beam (J. D. Scudder, personal communication, 1983), especially when one considers that the ratio of the typical beam density to total density is 10^{-3} [*Reinleitner et al.*, 1983]. Hence we do not feel that the lack of detection of the electron beam damages our explanation of the phenomena.

The geometry suggested by the observations in Figure 3 merits some attention. Recall that the interval of electrostatic burst activity extended over an interval of time when Voyager 2 was crossing the magnetic equator but that the chorus was limited to a shorter interval. In fact, the most intense chorus was located at $\lambda_m = 0°$. The theory of *Reinleitner et al.* [1983] and the acceleration considerations given by *Gurnett and Reinleitner* [1983] seem to fit these observations well. The electrons responsible for generating the electrostatic bursts may have been trapped and accelerated remotely, for example, at the equator, where the chorus waves are most intense. Even if the chorus emissions do not propagate far from the equator, however, the electrons have been accelerated along the field line and will continue to excite the bursts until the beam is dissipated or the electrons mirror. The question of how far the beam propagates before it dissipates is not easily answered. Usually, electron beams are observed to propagate much farther than one would predict from linear growth rate estimates. Presumably, some as of yet poorly understood nonlinear saturation mechanism limits the dissipation rate. Hence it is reasonable that one can find evidence for the electrostatic bursts without coincident observations of the chorus emission. The fact that modulation effects can still be seen in the absence of the chorus wave itself reflects the spatial bunching of the electrons that occurred during the acceleration.

As is the case with most other plasma wave phenomena detected at Jupiter and Saturn [*Scarf et al.*, 1979; *Gurnett et al.*, 1979, 1981; *Scarf et al.*, 1982; *Gurnett and Scarf*, 1983], chorus-induced electrostatic waves appear to be a universal planetary magnetospheric phenomenon. If, as *Gurnett and Reinleitner* [1983] and *Reinleitner et al.* [1983] speculate, Landau resonance interactions are important for the energization and precipitation of electrons, it is important to establish the role these interactions play in the magnetospheres of the giant planets as well as at earth.

Acknowledgments. We are grateful to E. C. Sittler, Jr., J. D. Scudder, and A. J. Lazarus of the Voyager plasma science team for the use of unpublished plasma data used in the interpretation of some of the events studied herein. We also wish to thank R. P. Lepping and the Voyager magnetometer team for providing magnetic field strengths required to determine the gyrofrequency for several of the events. This research was supported by the National Aeronautics and Space Administration through grants NAGW-337 and NGL-16-001-043 from NASA Headquarters, through contract 954013 with the Jet Propulsion Laboratory, and by the Office of Naval Research through grant N0014-76-C-0016.

The Editor thanks B. M. Pedersen and S. A. Curtis for their assistance in evaluating this paper.

REFERENCES

Briggs, R. J., *Electron-Stream Interaction With Plasmas, Res. Monogr. 29*, MIT Press, Cambridge, Mass., 1964.

Grabbe, C. L., A model for chorus-associated electrostatic bursts, *J. Geophys. Res.*, in press, 1983.

Gurnett, D. A., and L. A. Reinleitner, Electron acceleration by Landau resonance with whistler mode wave packets, *Geophys. Res. Lett.*, *10*, 603, 1983.

Gurnett, D. A., and F. L. Scarf, Plasma waves in the Jovian magnetosphere, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, p. 285, Cambridge University Press, New York, 1983.

Gurnett, D. A., and R. R. Shaw, Electromagnetic radiation trapped in the magnetosphere above the plasma frequency, *J. Geophys. Res.*, *78*, 8136, 1973.

Gurnett, D. A., W. S. Kurth, and F. L. Scarf, Plasma wave observations near Jupiter: Initial results from Voyager 2, *Science*, *206*, 987, 1979.

Gurnett, D. A., W. S. Kurth, and F. L. Scarf, Plasma waves near Saturn: Initial results from Voyager 1, *Science*, *212*, 235, 1981.

Kurth, W. S., F. L. Scarf, D. A. Gurnett, and D. D. Barbosa, A survey of electrostatic waves in Saturn's magnetosphere, *J. Geophys. Res.*, *88*, 8959, 1983.

Lepping, R. P., M. J. Silverstein, and N. F. Ness, Magnetic field measurements at Jupiter by Voyagers 1 and 2: Daily plots of 48 second averages, *NASA Tech. Memo.*, *83864*, 1981.

Reinleitner, L. A., D. A. Gurnett, and D. L. Gallagher, Chorus-related electrostatic bursts in the earth's outer magnetosphere, *Nature*, *295*, 46, 1982.

Reinleitner, L. A., D. A. Gurnett, and T. E. Eastman, Electrostatic bursts generated by electrons in Landau resonance with whistler mode chorus, *J. Geophys. Res.*, *88*, 3079, 1983.

Scarf, F. L., and D. A. Gurnett, A plasma wave investigation for the Voyager mission, *Space Sci. Rev.*, *21*, 289, 1977.

Scarf, F. L., D. A. Gurnett, and W. S. Kurth, Jupiter plasma wave observations: An initial Voyager 1 overview, *Science*, *204*, 991, 1979.

Scarf, F. L., D. A. Gurnett, and W. S. Kurth, Measurements of plasma wave spectra in Jupiter's magnetosphere, *J. Geophys. Res.*, *86*, 8181, 1981.

Scarf, F. L., D. A. Gurnett, W. S. Kurth, and R. L. Poynter, Voyager 2 plasma wave observations at Saturn, *Science*, *215*, 587, 1982.

Scarf, F. L., D. A. Gurnett, W. S. Kurth, and R. L. Poynter, Voyager plasma wave measurements at Saturn, *J. Geophys. Res.*, *88*, 8971, 1983.

Shaw, R. R., and D. A. Gurnett, A test of two theories for the low-frequency cutoffs of the nonthermal continuum radiation, *J. Geophys. Res.*, *85*, 4571, 1980.

D. A. Gurnett and W. S. Kurth, Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242.

L. A. Reinleitner, Max-Planck-Institut fur Aeronomie, Postfach 20, D-3411, Katlenburg-Lindau 3, Federal Republic of Germany.

(Received April 22, 1983;
revised August 26, 1983;
accepted September 20, 1983.)