

# A Comparison of the Plasma Wave Spectra for the Eight AMPTE Chemical Releases

H. C. KOONS

*Space Sciences Laboratory, The Aerospace Corporation, Los Angeles, California*

R. R. ANDERSON

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

The Active Magnetospheric Particle Tracer Explorers (AMPTE) IRM spacecraft performed a series of eight chemical releases in essentially comparable pairs. There were two lithium releases in the solar wind, two lithium and two barium releases in the near-Earth magnetotail, and two barium releases to simulate artificial comets, one in the solar wind and the other in the magnetosheath. A variety of plasma waves were observed in conjunction with each of the releases. Although there were unique features associated with some of the individual releases, the comparable releases generally produced similar wave emissions. This paper discusses the similarities and differences among the releases.

## INTRODUCTION

A major objective of the Active Magnetospheric Particle Tracer Explorers (AMPTE) spacecraft mission is the study of the local perturbations caused by the release of the tracer chemicals. The series of eight releases listed in Table 1 were conducted between September 11, 1984, and July 18, 1985. The mission is described by *Bryant et al.* [1985].

Two lithium releases were made in the solar wind upstream from the Earth's bow shock near the subsolar point. Two other lithium releases were made in the tail of the magnetosphere, one at a distance of  $18.7 R_E$  and the other closer to the Earth at  $12.1 R_E$ . Two barium releases were made for the purpose of creating an artificial comet. The first occurred on the dawnside of the Earth in the solar wind on December 17, 1984, and the second occurred on the duskside of the Earth in the magnetosheath on July 18, 1985. Two further barium releases took place in the relatively slow flowing plasmas in the magnetotail.

This series of eight chemical releases provided a unique opportunity to study the interaction of the ion clouds with the ambient plasma under paired sets of complementary conditions. Lithium was chosen because it is a light and very rare element suitable for the tracing experiments. It has a long ionization time (approximately 1 hour) and a high speed of expansion (4 km/s). Barium is a relatively heavy element with a short ionization time (about 28 s). This generates a strong perturbation in the ambient plasma.

The active experiments were essentially performed in pairs as listed in Tables 2 and 3. There were two lithium releases in the solar wind. There were two lithium releases in the magnetotail. There were two barium releases in rapidly flowing plasmas, one in the solar wind and the other in the magnetosheath. Finally, there were two barium releases in the magnetotail. The matrix of conditions is shown in Table 4.

Not only did this pairing allow for a unique opportunity to compare the results of two different chemicals (lithium and

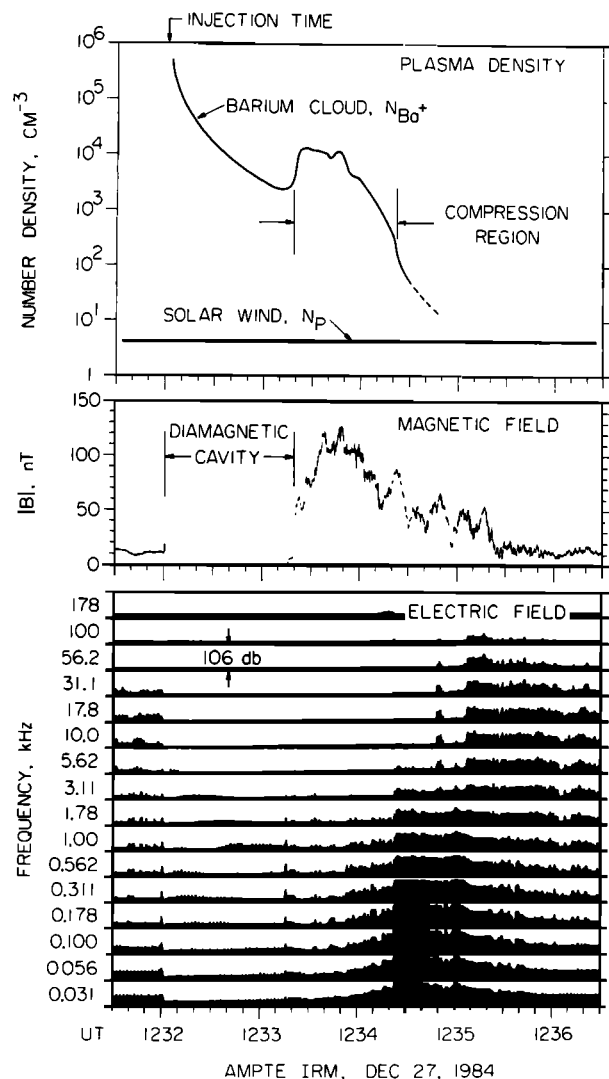


Fig. 1. A comparison of the electron density, magnetic field, and low-frequency electric field intensities from the barium "comet" release on December 27, 1984. The magnetic field is from *Lühr et al.* [1986]. The data in the bottom panel are from the ELF/MF spectrum analyzer [from *Gurnett et al.*, 1985, Figure 2].

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TABLE 1. AMPTE Chemical Releases

Date	Time, UT	Location	Chemical
Sept. 11, 1984	0725:03.5	solar wind	lithium
Sept. 20, 1984	0956:02	solar wind	lithium
Dec. 27, 1984	1232:00	solar wind	barium (comet I)
March 21, 1985	0920:33	tail	barium
April 11, 1985	0524:03	tail	lithium
April 23, 1985	0102:39	tail	lithium
May 13, 1985	0517:18	tail	barium
July 18, 1985	0400:08	magnetosheath	barium (comet II)

barium) under two different conditions (rapidly and slowly flowing ambient plasma), it also provided redundancy to verify that similar conditions produced similar results.

Two spacecraft, the Ion Release Module (IRM) and the United Kingdom Satellite (UKS), performed coordinated measurements in the vicinity of the chemical releases. The scientific instrumentation is summarized by *Bryant et al.* [1985]. The data presented in this paper are from the plasma wave experiment aboard the IRM. For a complete description of this instrument, see *Häusler et al.* [1985]. The electric antenna is an extendible beryllium-copper dipole element with a tip-to-tip length of 47.42 m. The nominal diameter of the element is 5 mm. The antenna is covered with an insulating layer out to a distance of 15.55 m on each half of the dipole. Four

separate instruments were used to collect the plasma wave data reported here. An ELF/MF spectrum analyzer provided by the University of Iowa covered the frequency range from 31.1 Hz to 178 kHz with 16 fixed frequency filters spaced logarithmically with bandwidths of approximately  $\pm 19\%$  up to a frequency of 1.78 kHz and  $\pm 11\%$  for the higher frequencies. A VLF/MF swept frequency receiver provided by The Aerospace Corporation covered the frequency range from 275 Hz to 99 kHz. This instrument has three separate 32-step spectrum analyzers and produces a spectrum from 275 to 2500 Hz every 2 s and from 1 kHz to 99 kHz every second. An HF stepped frequency receiver provided by the University of Iowa covered the frequency range from 100 kHz to 5.6 MHz in 42 discrete steps with a bandwidth of about 10 kHz. Finally, a wideband analog receiver transmits two frequency bands, 5 Hz to 1 kHz and 650 Hz to 10 kHz. Both channels incorporate automatic gain control.

WAVE ACTIVITY FOLLOWING THE CHEMICAL RELEASES

For the purpose of comparing the releases, the observations have been divided into seven phases. The data have been summarized in Tables 2 and 3.

The first phase is the initial encounter with the plasma formed by the prompt ionization and expansion of the released chemical. The initial contact with the plasma cloud is

TABLE 2. Summary of Plasma Waves Observed During the AMPTE Lithium Releases

	September 11, 1984	September 20, 1984	April 11, 1985	April 23, 1985
Type	Li solar wind	Li solar wind	Li tail	Li tail
Time, UT	0725:03	0956:02	0524:03	0102:39
Earth radii, $R_E$	18.7	18.9	18.7	12.1
Local time	1324	1242	2342	0034
Magnetic field, nT	6	8	11	38
IRM inside cavity, s	11	12.7	14	10
Entry boundary layer	yes	yes	N/A	yes
Broadband pulse	yes	yes	N/A	yes
Diamagnetic cavity	yes	yes	yes	yes
Ambient wave activity	no	no	no	no
Galactic radio noise	no	no	no	no
Kilometric radiation	no	no	no	no
Electron plasma frequency	yes	yes	yes	yes
Ion plasma frequency	weak	weak	no	no
Ion acoustic waves	weak	weak	weak	weak
Exit boundary layer	yes	yes	yes	yes
Broadband pulse	yes	yes	yes	yes
Magnetized plasma cloud	none	none	none	none
Ambient wave activity	...	...	...	...
Galactic radio noise	...	...	...	...
Kilometric radiation	...	...	...	...
Electron plasma frequency	...	...	...	...
Ion plasma frequency	...	...	...	...
Ion acoustic waves	...	...	...	...
Compression zone	yes	yes	none	none
Intense ion acoustic	yes	yes	...	...
Upstream	yes	yes	none	none
Ion acoustic	yes	yes	...	...
Electron cyclotron harmonic	no	yes	...	...
Electron plasma waves	...	...	...	...
Late time	none	none	yes	yes
Ion acoustic	...	...	yes	yes
Electron cyclotron harmonic	...	...	yes	yes
Electron plasma waves	...	...	...	...
Whistler mode waves	...	...	yes	yes

TABLE 3. Summary of Plasma Waves Observed During the AMPTE Barium Releases

	December 27, 1984	July 18, 1985	March 21, 1985	May 13, 1985
Type	Ba solar wind	Ba magnetosheath	Ba tail	Ba tail
Time, UT	1232:00	0400:08	0920:33	0517:18
Earth radii, $R_E$	17.2	18.7	12.0	14.4
Local time	0706	1806	2342	2300
Magnetic field, nT	11	20	8	17
IRM inside cavity, s	75	82	355	170
Entry boundary layer	yes	yes	yes	yes
Broadband pulse	yes	yes	yes	yes
Diamagnetic cavity	yes	yes	yes	yes
Ambient wave activity	no	no	no	no
Galactic radio noise	no	no	no	no
Kilometric radiation	no	no	no	no
Electron plasma frequency	yes	yes	yes	yes
Ion plasma frequency	yes	yes	yes	yes
Ion acoustic waves	yes	yes	weak	yes
Exit boundary layer	yes	yes	yes	yes
broadband pulse	yes	yes	yes	yes
Magnetized plasma cloud	none	none	yes	yes
Ambient wave activity	...	...	no	no
Galactic radio noise	...	...	no	no
Kilometric radiation	...	...	no	no
Electron plasma frequency	...	...	yes	yes
Ion plasma frequency	...	...	no	no
Ion acoustic waves	...	...	weak	yes
Compression zone	yes	yes	none	none
Intense ion acoustic	yes	yes	...	...
Upstream	yes	none	none	none
Ion acoustic	no	...	...	...
Electron cyclotron harmonic	no	...	...	...
Electron plasma waves	yes	...	...	...
Late time	yes	none	none	none
Ion acoustic	no	...	...	...
Electron cyclotron harmonic	no	...	...	...
Electron plasma waves	yes	...	...	...
Whistler mode waves	no	...	...	...

marked by a short broadband electrostatic pulse with frequencies below the ion gyrofrequency. An example is shown at 1232 UT in Figure 1. The pulse is believed to be generated by a modified-two-stream instability of the electron current flowing on the boundary of the diamagnetic cavity [Häusler *et al.*, 1986]. This electrostatic pulse was observed for the seven releases for which data are available from the instant of the release. The receivers were not turned on for the first few seconds after the lithium release on April 11, 1985.

The second phase is the diamagnetic cavity formed by the exclusion of the ambient magnetic field from the interior of the highly conducting plasma cloud [Lühr *et al.*, 1986]. One such diamagnetic cavity is clearly seen in the magnetic field data shown in Figure 1. The IRM was in this cavity for varying lengths of time following each of the chemical releases. For the lithium releases, this time was typically short, of the order of 10 s. The time was longer, ranging from 75 to 355 s, for the barium releases. This phase is marked by the cessation of all ambient wave activity. Electromagnetic waves such as galactic radio noise and terrestrial kilometric radiation are excluded from the cavity at frequencies below the electron plasma frequency by the outer (high density) shell of the plasma cloud. Ion acoustic wave emissions in the cavity are generally quite weak and are probably related to the presence of the plasma cloud. The most prominent feature in the wave data is the Langmuir wave emissions at the local electron plasma frequency. This feature shows up well in both the HF spectrum

analyzer for frequencies above 100 kHz and the VLF/MF stepped frequency receiver at frequencies below 100 kHz. An example from the barium release on December 27, 1984, is shown in Figure 2. The electron plasma frequency is the monotonically decreasing line identified as  $f_p$  in Figure 2. Häusler *et al.* [1986] report that the measured amplitude for these waves is consistent with that expected for thermal fluctuations. A second feature which is typically weak for the lithium releases but strong for the barium releases is a line near the ion plasma frequency. This feature shows up well in both the VLF/MF stepped frequency data and the wideband analog data from all of the barium releases. An example from the barium "comet" release in the solar wind on December 27, 1984, is the monotonically decreasing line visible in the middle and lower frequency ranges of the spectrogram from the swept frequency receiver from 1232 to 1233 UT in Plate 1. A higher-resolution spectrogram of this same emission from the wideband receiver is shown in Figure 4 of Gurnett *et al.* [1985].

TABLE 4. Matrix of Experimental Conditions

	Barium	Lithium
Mass	heavy	light
Ionization time	short	long
Rapid flow	solar wind and magnetosheath	solar wind
Quiescent flow	magnetotail	magnetotail

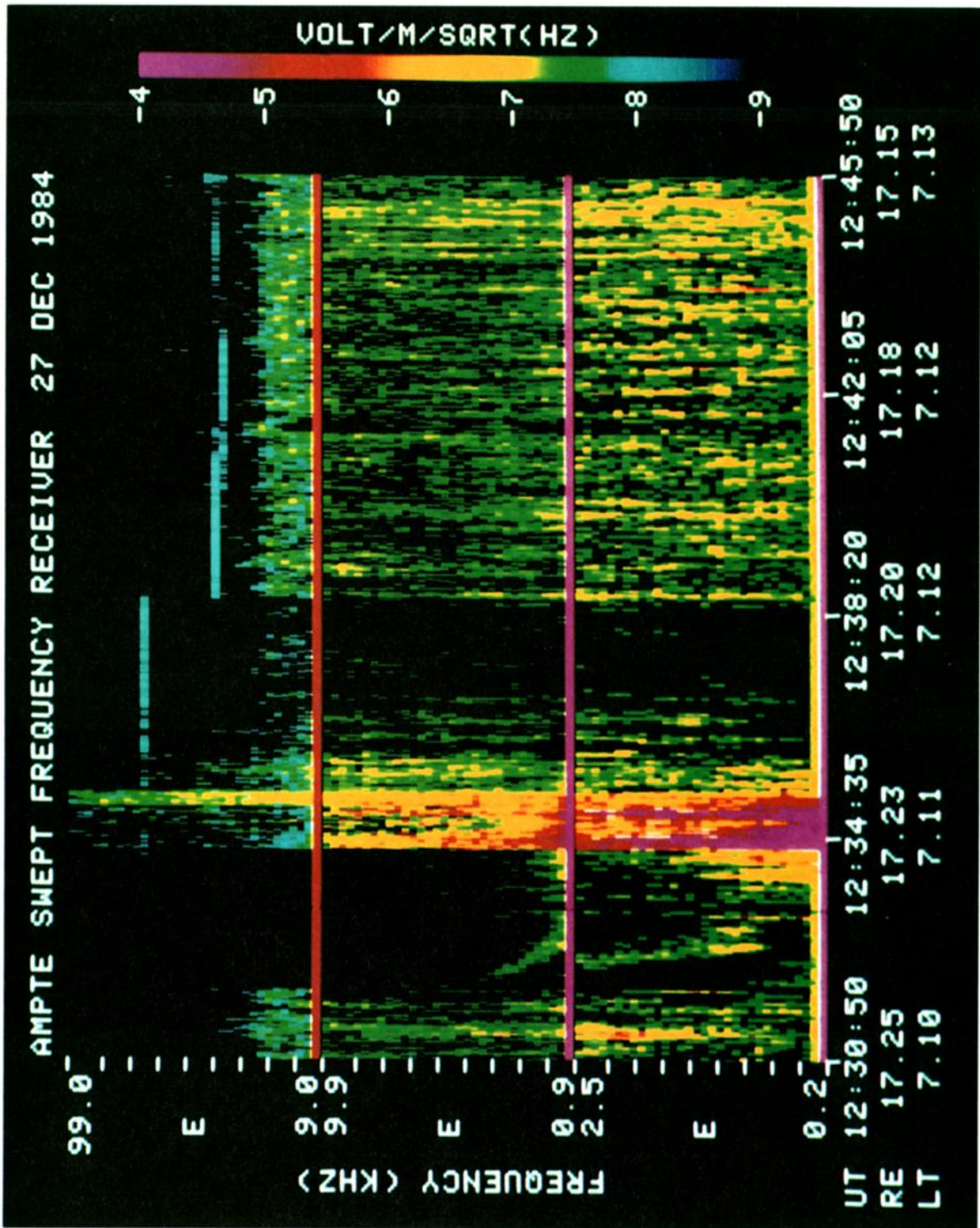


Plate 1. Spectrogram from the VLF/MF swept frequency receiver for the barium "comet" release on December 27, 1984. Each of the three panels displays data from the electric field antenna over a linear frequency range.

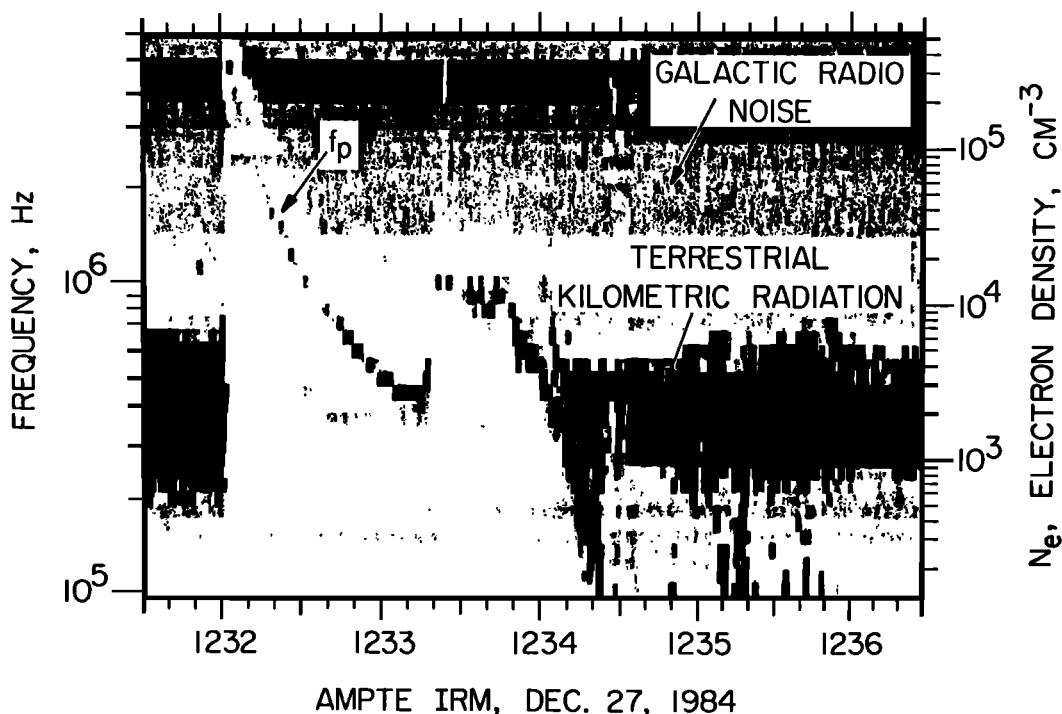


Fig. 2. A frequency-time spectrogram from the high-frequency swept frequency receiver during the solar wind barium release on December 27, 1984. The ion cloud formed by the explosion blocked the galactic and terrestrial radio noise and produced the depressed noise levels evident from 1232:02 to about 1234:20 UT. The electron plasma oscillation line, labeled  $f_p$ , gives the electron density, as indicated by the scale on the right side of the plot [from Gurnett *et al.*, 1985, Figure 1].

Although the excitation mechanism for this emission is not known, it is likely that the waves are ion acoustic waves [Gurnett *et al.*, 1985]. The ion acoustic mode has an upper cutoff frequency at the ion plasma frequency. The waves may be thermally excited. The waves just below the cutoff are expected to be strongest because they are the least damped. The frequency of these waves is modulated at the spin rate of the satellite. This peculiar behavior suggests that the waves may be related to the presence of the spacecraft.

The third phase is the crossing of the boundary layer upon exiting the diamagnetic cavity. The spacecraft exits the cavity because the plasma cloud picks up momentum from the ambient plasma and is convected over the spacecraft, which has a velocity less than 1 km/s. The broadband pulse observed at this second crossing of the boundary is very similar to the pulse measured when the cloud is first encountered. This pulse can be seen at 1233:30 UT in Figure 1. It was detected for all of the eight releases.

The fourth phase occurs only for the barium releases in the tail. Because the flow of ambient plasma around the plasma cloud is very slow, there is little transfer of momentum to the cloud, and the diamagnetic phase ends long before the barium ion density reaches the ambient background density. Under these conditions there is a high-density, magnetized, barium plasma cloud that lasts for about 20 min. The wave activity inside this magnetized cloud is similar to the wave activity during phase two inside the magnetic cavity with the exception that there are no emissions specifically related to the ion plasma frequency. The spectrogram in Plate 2 shows the electron plasma frequency emission decreasing from 99 kHz to about 5 kHz following the barium release on May 13, 1985. The natural electromagnetic radiation appears above the elec-

tron plasma frequency as the plasma frequency in the cloud drops below the frequency of the natural emissions and they penetrate the cloud to the location of the spacecraft.

The fifth phase is the compression zone in front of the cloud. This is the region where the magnetic field piles up as it drapes around the cloud [Lühr *et al.*, 1986]. For the solar wind releases, the magnetic field is measured to be several times larger than the ambient solar wind magnetic field. The region is only observed in the solar wind and magnetosheath releases. An example occurs in Figures 1 and 2 about 1234:35 UT. An intense burst of electrostatic noise is observed near the upstream edge of this compression region. This noise is very similar to the electrostatic noise observed at the Earth's bow shock. This noise is among the most intense ever measured by a space plasma wave experiment. An electric field intensity of 140 mV/m was measured for the noise in front of the barium comet release on December 27, 1984. Analysis shows that this noise can be accounted for by a beam-plasma instability caused by the solar wind proton beam streaming through the nearly stationary lithium or barium cloud [Gurnett *et al.*, 1985].

The sixth phase occurs upstream of the ion cloud in the solar wind after the compression region has convected past the spacecraft. This region is only observed for the solar wind lithium releases. Here the density of the injected ions is less than the ambient solar wind density. The observations differ more during this phase than during the earlier phases. During the first lithium release on September 11, 1984, strong ion acoustic waves were observed during this phase. During the second lithium release on September 20, 1984, both ion acoustic and electron cyclotron harmonic (ECH) waves were observed. The spectrogram is shown in Plate 3. The ion acoustic

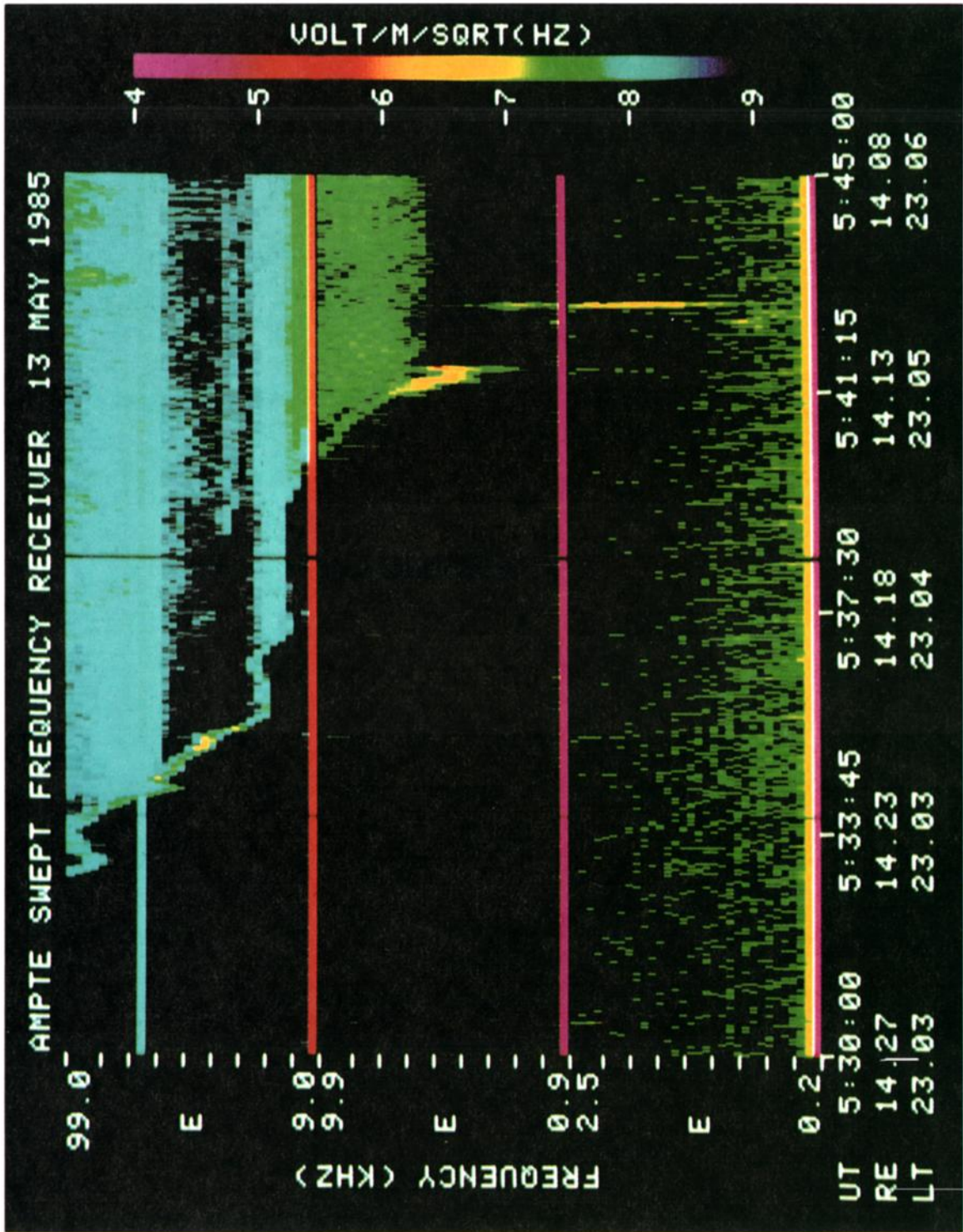


Plate 2. Spectrogram from the VLF/MF swept frequency receiver for the barium magnetotail release on May 13, 1985. Each of the three panels displays data from the electric field antenna over a linear frequency range.

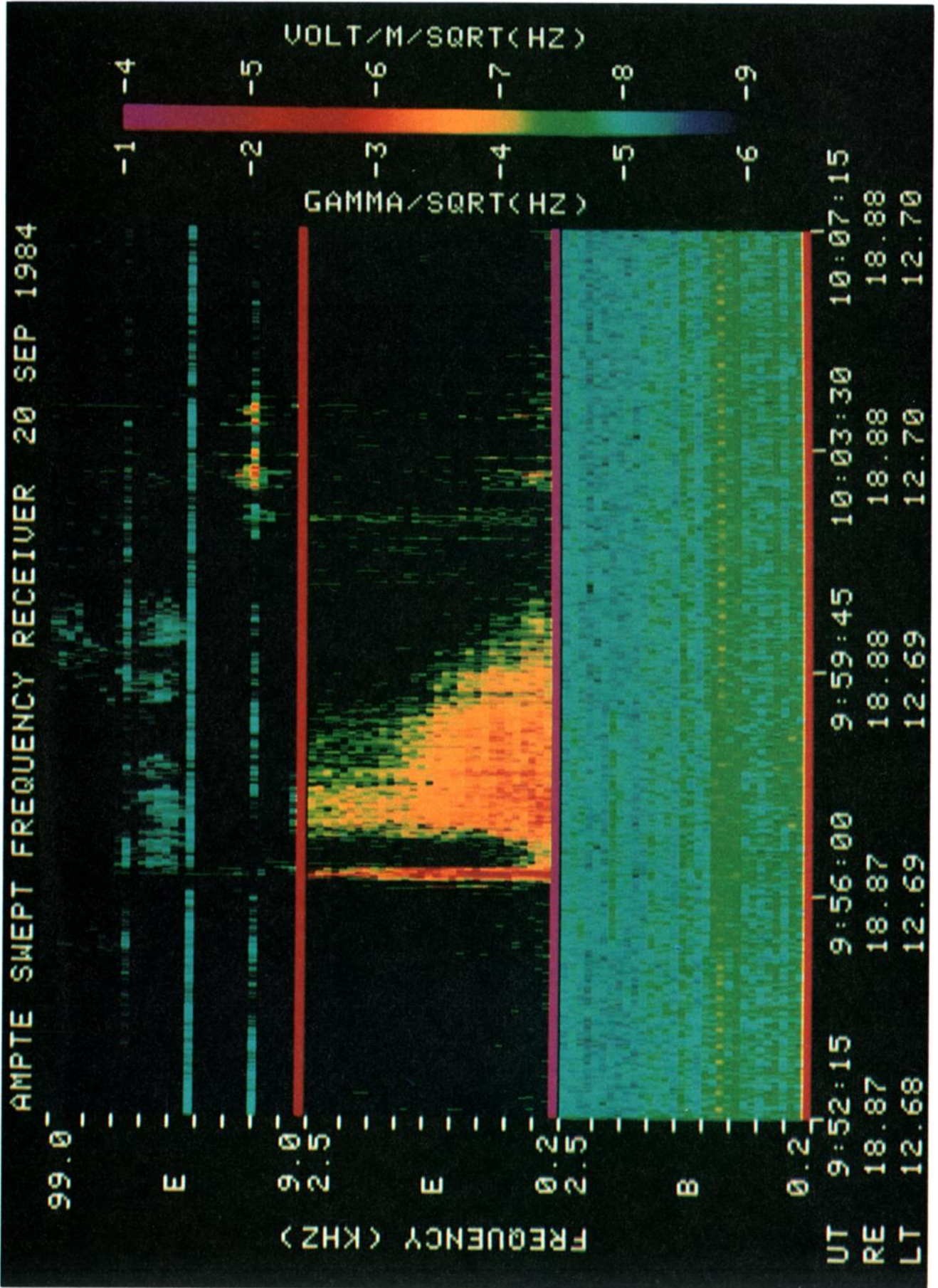


Plate 3. Spectrogram from the VLF/MF swept frequency receiver for the lithium solar wind release on September 20, 1984. The top two panels display data from the electric antenna; the bottom panel displays data from the magnetic antenna [from Roeder *et al.*, 1987, Plate 1].

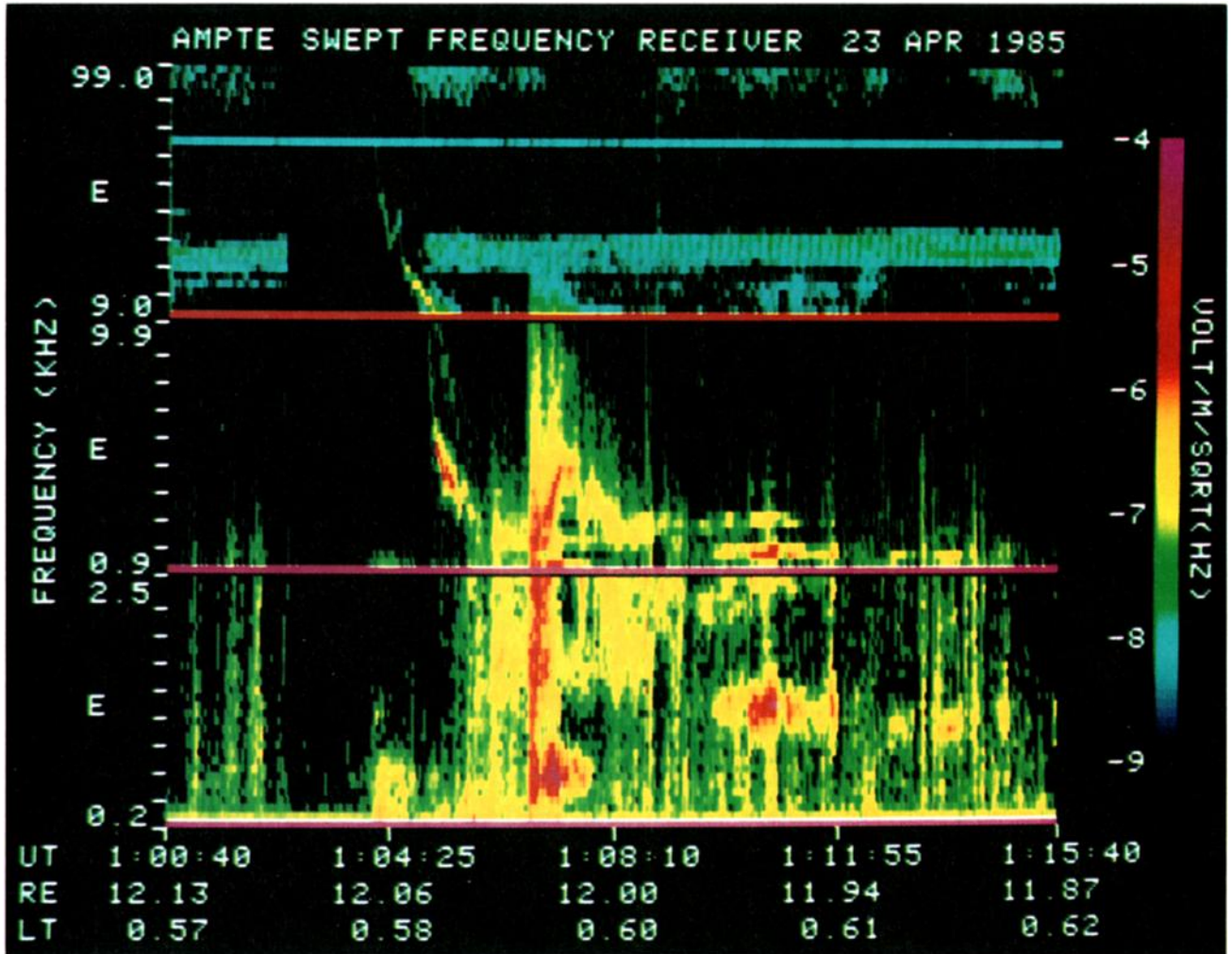


Plate 4. Spectrogram from the VLF/MF swept frequency receiver for the lithium magnetotail release on April 23, 1985. Each of the three panels displays data from the electric field antenna over a linear frequency range.

waves were nearly isotropic while the ECH waves were nearly perpendicular to the local magnetic field. The ECH waves are believed to be driven by the energetic lithium ions accelerated by the solar wind induced electric field [Roeder *et al.*, 1987].

Finally, in the last phase we observe wave activity that appears to be associated with the injection on a longer time scale after the lithium releases in the magnetotail. The spectrogram in Plate 4 shows ion acoustic waves, ECH waves, and possibly some whistler mode wave activity near one half of the electron gyrofrequency from 5 to 8 min after the lithium release in the magnetotail on April 23, 1985. This spectrogram should be compared with the one in Plate 3. The time scale may be lengthened by the slower decrease in plasma density within the cloud.

#### CONCLUSION

The eight chemical release experiments performed by the AMPTE mission provided a unique opportunity to observe and compare the wave activity under a variety of ambient plasma conditions. The experiments were conducted in pairs. The emissions detected following each of the releases in a comparable pair were quite similar. This is convincing evidence that they are not isolated observations but are fundamental to the interaction between the injected plasma and the ambient plasma. Most of the emissions that were observed have been at least tentatively identified.

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R. R. Anderson, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242.

H. C. Koons, The Aerospace Corporation, MS M2-260, P. O. Box 92957, Los Angeles, CA 90009.

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