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PLASMA WAVES ASSOCIATED WITH THE AMPTE ARTIFICIAL COMET

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Abstract. Numerous plasma wave effects were detected by the AMPTE/IRM spacecraft during the artificial comet experiment on December 27, 1984. As the barium ion cloud produced by the explosion expanded over the spacecraft, emissions at the electron plasma frequency and ion plasma frequency provided a determination of the local electron density. The electron density in the diamagnetic cavity produced by the ion cloud reached a peak $\geq 5 \times 10^5$ cm^{-3}, then decayed smoothly as the cloud expanded, varying approximately as t^{-2}. As the cloud began to move due to interactions with the solar wind, a region of compressed plasma was encountered on the upstream side of the diamagnetic cavity. The peak electron density in the compression region was about 1.5×10^4 cm^{-3}. Later, a very intense (140 mVolt/m) broadband burst of electrostatic noise was encountered on the sunward side of the compression region. This noise has characteristics very similar to noise observed in the earth's bow shock, and is believed to be a shock-like interaction produced by an ion beam-plasma instability between the nearly stationary barium ions and the streaming solar wind protons.

Introduction

Measurements from the AMPTE (Active Magnetospheric Particle Tracer Explorers) program have now provided the first investigation of plasma effects produced by artificial gas releases in the solar wind, thereby simulating some of the processes thought to occur in natural comets. This report presents an overview of the results from the plasma wave investigation on the AMPTE/IRM (Ion Release Module) spacecraft during the artificial comet experiment on December 27, 1984. For a detailed description of the plasma wave instrument on the IRM, see Häusler et al. [1985a].

During the artificial comet experiment two canisters of barium were released from the IRM on the morning side of the earth at a geocentric radial distance of about 17.2 R_E. Ten minutes after the release, at 1232 UT, the two canisters were exploded simultaneously at a distance of about 0.87 km from the spacecraft. The explosion produced a rapidly expanding cloud of barium which swept over the spacecraft a fraction of a second later. Ultraviolet radiation from the sun then ionized the gas, forming a dense expanding cloud of ionized barium.

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The Plasma Density Profile

The plasma density can be determined at the IRM from the blockage of external electromagnetic radiation by the plasma cloud, and from locally excited plasma oscillations within the cloud. At high frequencies, above about 100 kHz, the arrival of the ion cloud is associated with an abrupt drop in the electric field intensities at about 1232:01 UT (Universal Time). This effect can be clearly seen in Figure 1, which shows a frequency-time spectrogram covering the frequency range from 100 kHz to 5.6 MHz. The intensity drop is caused by the high electron density in the cloud which blocks the external galactic and terrestrial radio emissions at frequencies below the electron plasma frequency, f_p. As is well known [Krall and Trivelpiece, 1973], electromagnetic radiation cannot propagate in a plasma at a frequency below the electron plasma frequency, which is given by $f_p = 9000\sqrt{N_e}$ Hz, where N_e is the electron number density in cm^{-3}.

Shortly after the arrival of the ion cloud a narrowband emission can be seen in Figure 1 sweeping downward in frequency with increasing time. Emissions of this type have been detected in numerous space plasma wave experiments, and are caused by electrostatic oscillations at the

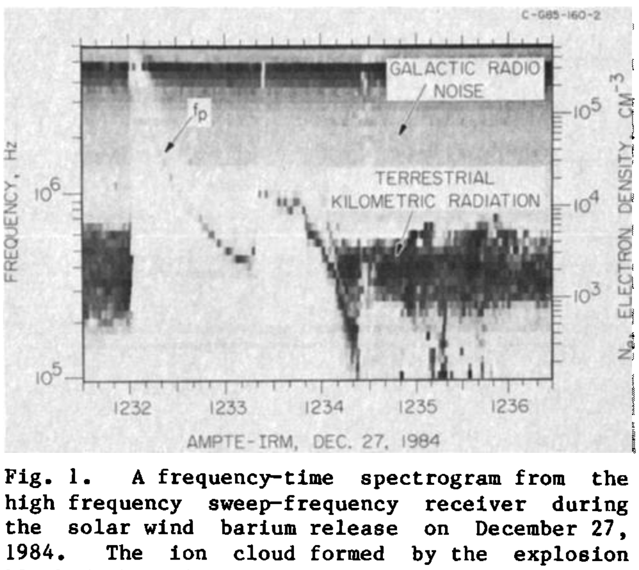

Fig. 1. A frequency-time spectrogram from the high frequency sweep-frequency receiver during the solar wind barium release on December 27, 1984. The ion cloud formed by the explosion blocked the galactic and terrestrial radio noise and produced the depressed noise levels evident from 1232:02 to about 1234:20. The electron plasma oscillation line, labelled f_p, gives the electron density, as indicated by the scale on the right-hand side of the plot.

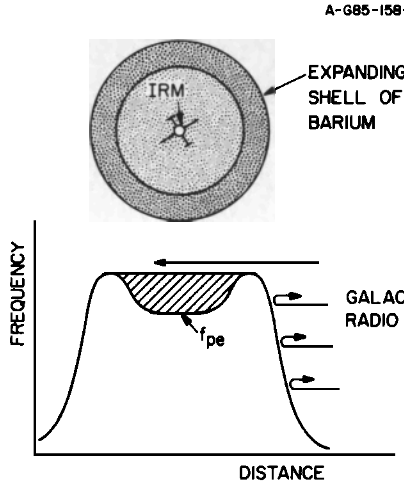

Fig. 2. A sketch of the ion cloud geometry deduced from the plasma wave data during the initial stages of the expansion. The shell-like geometry explains why the low frequency cutoff of the galactic background in Figure 1 is above the local electron plasma frequency, f_p.

electron plasma frequency [Krall and Trivelpiece, 1973]. These oscillations are probably excited by thermal fluctuations in the plasma [Hoang et al., 1980]. Since the electron plasma frequency depends only on the electron density, the emission frequency gives a direct measurement of the local electron density. The electron density is shown by the scale on the right-hand side of Figure 1. The peak density exceeds 5×10^5 cm^{-3}. Since the barium ions are singly charged and the plasma is electrically neutral the electron density also gives the ion density, $N_e = N_i$.

After the arrival of the ion cloud the plasma density decreases smoothly for about one minute, to about 1233. During this phase the density is mainly controlled by the ionization and expansion of the ion cloud and varies approximately as t^{-2}. From careful examination of the spectrogram, one can see that the galactic noise background has a propagation cutoff which is about a factor of two above the local electron plasma frequency. Our initial interpretation is that the ejected ion cloud has a shell-like configuration such as illustrated in Figure 2. The cross-hatched region is inaccessible to radiation arriving from outside the ion cloud. Therefore, the propagation cutoff in the inaccessible region is above the local electron plasma frequency. Barium cloud explosions at low altitudes in the ionosphere have been observed to produce a shell-like density structure of the type shown in Figure 2.

As the ion cloud expands it begins to move due to forces exerted by the solar wind. The first evidence of a transition from a temporal to a translational dependence is at 1233:15, where the density suddenly increases. The density variations in this region are illustrated more clearly in the top panel of Figure 3, which shows the plasma density profile scaled from the plasma frequency emission in Figure 1. For comparison, the middle panel shows the magnetic field strength from the magnetometer on the IRM. The diamagnetic cavity produced by the dense highly conducting plasma cloud is clearly evident in the magnetometer data. As can be seen by comparing the two plots, the density increase at 1233:15 coincides with an increase in the magnetic field strength as the spacecraft passes through the boundary of the diamagnetic cavity. This region of high density and strong field is caused by the "pileup" of plasma around the nose of the cloud and "draping" of magnetic field lines around the diamagnetic cavity.

Waves in the Diamagnetic Cavity

The wave intensities in the diamagnetic cavity are quite low, generally lower than in the undisturbed solar wind. The waves that do exist in the diamagnetic cavity are best seen in the bottom panel of Figure 3, which shows the electric field intensities from a 16-channel analyzer which covers the frequency range from 31 Hz to 178 kHz. The intensity scale in the bottom panel

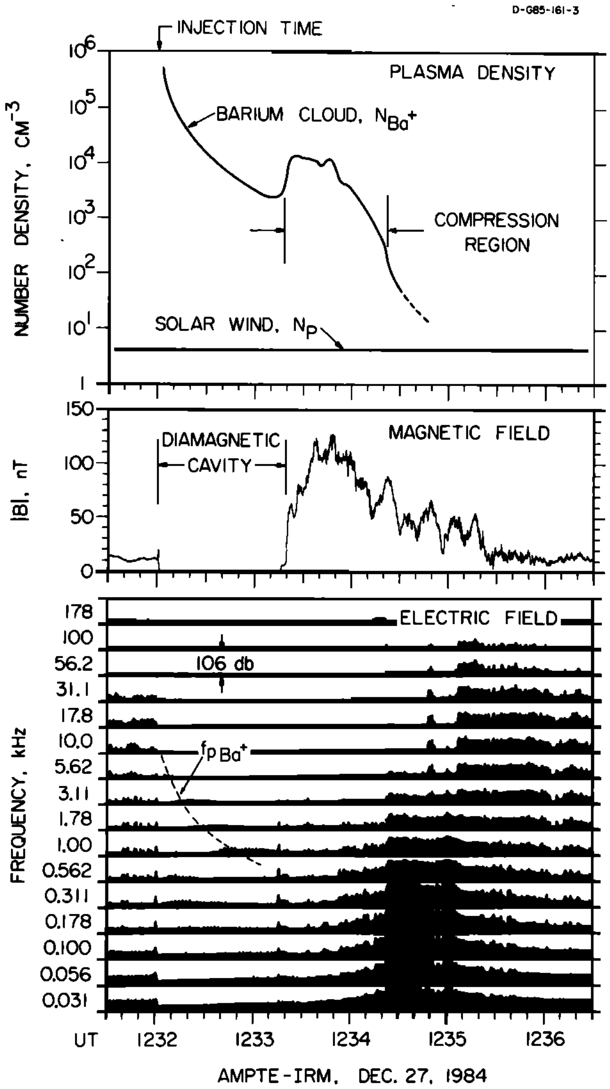

Fig. 3. A comparison of the electron density, magnetic field, and low frequency electric field intensities. The intense noise from about 1234 to 1236 is believed to be due to a shock-like interaction near the upstream edge of the ion cloud.

of Figure 3 is logarithmic and covers a dynamic range of 106 db, from 0.5 μVolts/m to 100 mVolts/m. Within the diamagnetic cavity two narrow bands of noise can be seen sweeping downward in frequency with increasing time, the first starting at about 5.62 kHz and sweeping down to about 1 kHz, and the second starting at about 1.0 kHz and sweeping down to about 178 Hz. Further details of the two narrowband emissions are illustrated in Figure 4, which shows high resolution frequency-time spectrograms of the wideband waveform data obtained during this period. The wideband data provide very high frequency and time resolution but tend to destroy amplitude information because an automatic gain control is used in the transmission process. The 0 to 10 kHz spectrogram shows the upper of the two emission bands and the 0 to 1 kHz spectrogram shows the lower band. The center frequency of the upper emission band is almost exactly at the barium ion plasma frequency. The barium ion plasma frequency is given by dividing the electron plasma frequency by the square root of the ion to electron mass ratio, $\sqrt{m_{Ba}/m_e} = 501$. The emission band near the barium ion plasma frequency has considerable fine structure, some of which appears to be controlled by the antenna rotation (spin period, 4.3 seconds). The lower emission band has not been associated with any known characteristic frequency of the plasma.

At the present time the origin of the two low frequency emission bands in the diamagnetic cavity remains unknown. One possibility is that the waves are ion acoustic waves. It is well known that the ion acoustic mode has an upper frequency cutoff at the ion plasma frequency, which suggests a relationship with the upper emission band [Krall and Trivelpiece, 1973]. Normally ion acoustic waves near this cutoff have very short wavelengths (near the Debye length), and are strongly damped. However, for large electron to ion temperature ratios, $T_e/T_i >> 1$, such as probably exist in the diamagnetic cavity, the damping is reduced and waves can in principle occur near the ion plasma frequency. If such waves do exist the wavelengths would be very short, only a fraction of a meter.

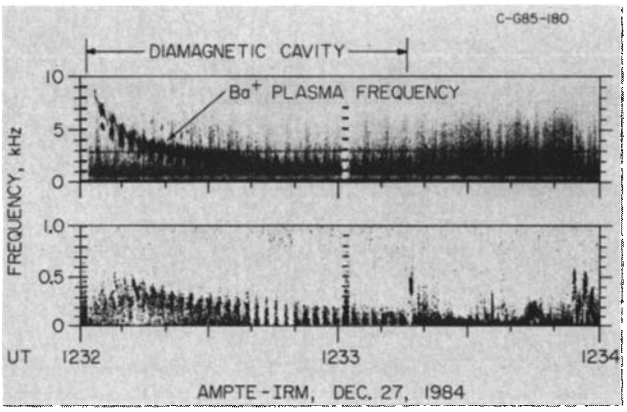

Fig. 4. High resolution spectrograms showing details of the two low frequency narrowband emissions inside the diamagnetic cavity. The emission in the upper panel is at the barium ion plasma frequency.

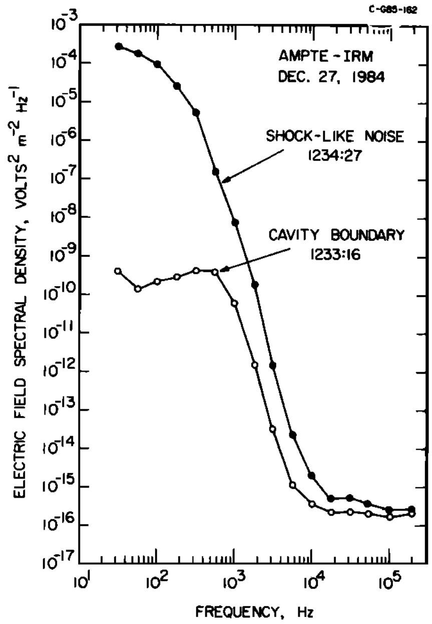

Fig. 5. Electric field spectrums of the electrostatic observed at the boundary of the diamagnetic cavity (1233:16) and in the shock-like interaction region upstream of the ion cloud (1234:27).

Waves Outside the Diamagnetic Cavity

As the spacecraft crosses the boundary of the diamagnetic cavity an abrupt burst of noise occurs across a broad range of frequencies at 1233:16. The spectrum of this noise is shown in shown in Figure 5. The location of this burst suggests that the noise may be driven by the electron magnetization current that flows along the boundary of the diamagnetic cavity. A good candidate for the instability involved would be the current-driven ion acoustic instability [Krall and Trivelpiece, 1973]. Since the intensity of this noise is quite weak, only about 500 μVolts/m, it is unlikely that this noise plays a significant role in the dynamics of the ion cloud.

As the ion cloud moves farther away from the spacecraft, a much more intense burst of noise is seen near the upstream edge of the compression region. This noise extends across a broad range of frequencies, from below 31 Hz up to about 10 kHz, and is so intense that it saturates some of the low frequency channels. A similar type of electrostatic noise was observed during the two previous solar wind lithium releases [Hausler et al., 1985b]. A spectrum of the intense electrostatic noise is shown in Figure 5. This spectrum is a four-second average starting at 1234:27, near the time of maximum intensity. The 100-, 178-, and 311-Hz channels are saturated, so the intensities in these channels are probably slightly higher than shown. As can be seen, most of the energy is at frequencies below a few hundred Hz. The broadband electric field strength, integrated over all the frequency channels is about 140 mVolts/m. These electric field intensities are among the most intense ever detected by a space plasma wave experiment.

Our current belief is that the intense burst of electrostatic noise near the upstream boundary of the compression region is caused by a shock-like interaction between the injected barium ions and the rapidly flowing solar wind protons. Because of their large cyclotron radii (40 to 400 km), the solar wind protons stream directly into the ion cloud. Since the injected barium ions are essentially at rest, the resulting ion velocity distribution function has two peaks, one caused by the barium ions, and the other by the solar wind protons. It has been established [Gurnett et al., 1985] that this type of double-humped velocity distribution function is unstable and that electrostatic waves develop which quickly grow to large amplitudes. The highest growth rates occur when the injected ion density is comparable to the solar wind density, which explains why the noise only occurs near the outer edge of the ion cloud. Deep within the ion cloud the solar wind proton density is too small for instability to occur, and far upstream the barium ion density is too small.

It is not clear what role the intense electrostatic noise plays in the overall interaction of the barium cloud with the solar wind. A somewhat similar type of noise is observed at the earth's bow shock, apparently caused by ions reflected from the shock [Gurnett, 1985]. In the case of a shock the electrostatic noise is believed to be the primary mechanism for energy dissipation in the shock and is therefore an essential feature of the shock. It is possible that the noise observed upstream of the AMPTE artificial ion clouds is also associated with a shock-like interaction. Many of the characteristics of a shock are present, including (i) a decrease in the solar wind velocity, (ii) an increase in the plasma density, and (iii) energy dissipation. However, if a shock is present then it is probably not a conventional magnetohydrodynamic (MHD) shock, because the ion cyclotron radii are comparable to the radius of the cloud and mass loading due to ionization may be important. The most likely possibility is that the noise is associated with an electrostatic shock. Noise somewhat similar to that detected by the AMPTE/IRM has been observed in association with electrostatic shocks generated in laboratory plasmas [Ikezi et al., 1973].

Even farther upstream, from about 1235:10 to 1237, yet another type of noise is evident in the 5.62 to 56.2 kHz channels of Figure 3. This noise is near the solar wind electron plasma frequency, which is about 25 kHz, and is clearly distinguishable from the intense shock-like electrostatic noise at lower frequencies. Our initial interpretation is that this noise is caused by electron plasma oscillations excited by electrons streaming away from the ion cloud. Somewhat similar plasma oscillations are observed upstream of the earth's bow shock [Scarf et al., 1971, and are known to be produced by suprathermal electrons streaming away from the shock.

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