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During the Galileo flyby of Venus the plasma wave instrument was used to search for impulsive radio signals from lightning and to investigate locally generated plasma waves. A total of nine events were detected in the frequency range from 100 kilohertz to 5.6 megahertz. Although the signals are weak, lightning is the only known source of these signals. Near the bow shock two types of locally generated plasma waves were observed, low-frequency electromagnetic waves from about 5 to 50 hertz and electron plasma oscillation at about 45 kilohertz. The plasma oscillations have considerable fine structure, possibly because of the formation of soliton-like wave packets.

THE OCCURRENCE OF LIGHTNING IN the atmosphere of Venus has been reported by several investigators but still remains controversial. The existence of lightning at Venus is important because it is indicative of convective storms in the atmosphere. Also, lightning may be an indicator of active volcanism. The previous reports of lightning at Venus include various measurements of impulsive low-frequency (<80 kHz) radio signals from the Venera landers (*1*) and observations of very low-frequency (~100 Hz) whistler signals from the Pioneer-Venus orbiter (*2*). For the Venera data there has always been a concern that the signals could have been caused by locally induced electrostatic discharges as the spacecraft descended through the atmosphere, and for the Pioneer-Venus data the whistler interpretation has been criticized on the grounds that the signals could have been caused by various types of locally generated plasma waves (*3*). The Galileo observations now provide strong evidence that lightning does exist in the atmosphere of Venus.

The Galileo flyby of Venus provided an excellent opportunity to search for radio signals from lightning. As described by Gurnett *et al.* (*4*), the Galileo plasma wave

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instrument provides electric field measurements at frequencies up to 5.6 MHz. This frequency range is well above the frequency range of all previous radio and plasma wave measurements at Venus. At these high frequencies, it is possible to detect radio signals escaping through the ionosphere at frequencies above the ionospheric propagation cutoff. Lightning was identified at Saturn and Uranus (*5*) with this technique. Because the measurements are made at frequencies well above the local electron plasma frequency, this approach has the advantage that the signals can easily be distinguished from locally generated plasma waves, thereby avoiding the controversy that plagued the interpretation of the Pioneer-Venus data.

Unfortunately, high-frequency lightning measurements have certain disadvantages and limitations that must also be considered. Because the spectrum of lightning varies approximately as f^{-2}, where f is the frequency, the signal strength decreases rapidly with increasing frequency. Because of this frequency dependence, the best chance for detecting radio signals from lightning is from signals escaping through regions of the ionosphere where the propagation cutoff frequency is very low, such as on the night side of the planet. A plausible lower limit to the night side ionospheric cutoff frequency is on the order of several hundred kilohertz. The frequency range of primary interest is therefore from a few hundred kilohertz to a few megahertz.

Because the integration time constant of the Galileo high-frequency receiver (~70 ms) was not ideally suited for detecting lightning, a study of mid-latitude terrestrial lightning was carried out with an engineering model to evaluate the sensitivity of the instrument to lightning. After correction for the typical radial distances (~4 to 5 R_V) at which the Venus data were obtained, these studies showed that the expected peak signal-to-noise ratio for signals comparable to terrestrial lightning would be about 10 dB at 100 kHz, decreasing to 0 dB at 300 kHz. Thus, if lightning at Venus is comparable to mid-latitude terrestrial lightning, it would be just barely detectable.

Because of various temperature limitations, the plasma wave instrument could only be operated for ~1 hour near Venus. To optimize the possibility of detecting both lightning and waves associated with the bow shock, all of the data were acquired on the night side of Venus, shortly before closest approach. The data acquisition interval actually achieved was 53 min, from 0432 to 0525 universal time (UT) on 10 February 1990. The search for lightning was carried out using data from the high-frequency receiver, which consists of 42 channels covering the frequency range from 100.8 kHz to 5.65 MHz.

The output from a typical channel (1.008 MHz) is illustrated in Fig. 1, which shows the transmitted data number (that is, the digitized value) on the scale to the right and the corresponding signal intensity on the scale to the left. The nearly constant level across the plot, at an intensity of about 4.5×10^{-17} V^2 m^{-2} Hz^{-1} with fluctuations of about ±2 data numbers, is characteristic of the receiver noise level. The smoothly varying enhancement near the end of the plot, from about 0520 to 0525 UT, is caused by a type III solar radio burst, which is easily identified at these frequencies. An impulsive event, typical of what one expects from lightning, can be seen near the beginning of the plot, at about 0434 UT.

Impulsive events of this type are very rare. To identify impulses, we developed an algorithm to search for large values of the quantity $\delta = 2N_n - (N_{n-1} + N_{n+1})$, where

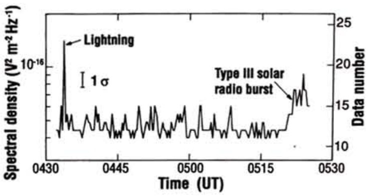

Fig. 1. The electric field intensity in a representative channel (1.008 MHz) from the high-frequency spectrum analyzer.

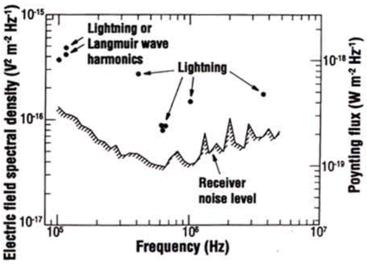

Fig. 2. The spectrum of the nine impulsive events detected during the Venus flyby. The receiver noise level is based on in-flight measurements.

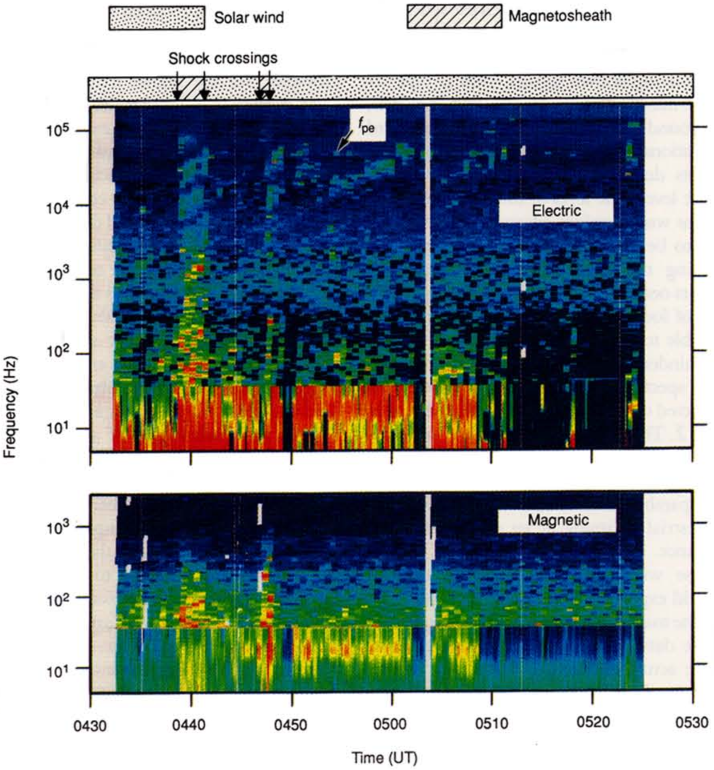

Fig. 3. Frequency-time spectrograms of the electric and magnetic intensities measured by the medium- and low-frequency spectrum analyzers. The intensities are color-coded, with red the most intense and blue the least intense.

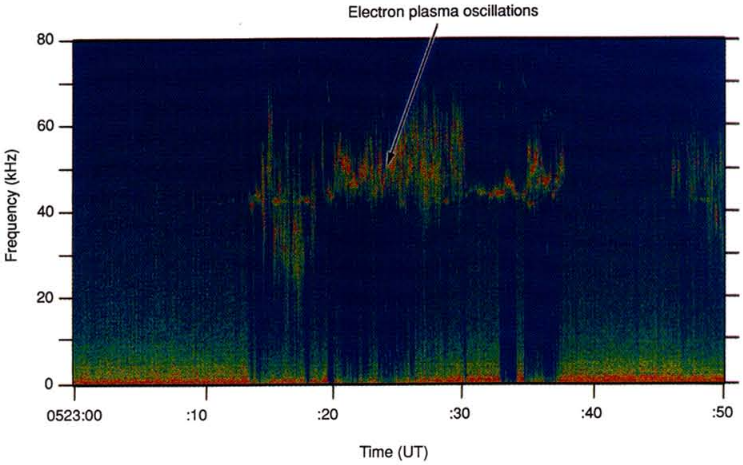

Fig. 4. A high-resolution frequency-time spectrogram of the electron plasma oscillations.

N_{n-1}, N_n, and N_{n+1} are successive data numbers in a given channel. Events were only counted if δ exceeded a threshold. We set the threshold by considering two 1-hour control intervals, one before and one after the Venus flyby, during which the spacecraft was operating in the same mode as at Venus (dual spin, all instruments operating). After eliminating known signals, such as type III radio bursts and known interference signals, we found that a threshold of four standard deviations completely eliminated all false events due to fluctuations in the receiver noise level. The level of four standard deviations was therefore adopted as the threshold to be used in the search for lightning. During the Venus flyby, nine impulsive events occurred with δ exceeding the threshold of four standard deviations, three comparable to the one shown in Fig. 1 and the remainder of somewhat smaller amplitudes.

A spectrum of the nine impulsive events detected during the Venus flyby is shown in Fig. 2. The intensities are all very low, only slightly above the receiver noise level. Although the intensities are low, they are comparable to what one would expect from terrestrial lightning at an equivalent radial distance. The intensities also tend to decrease with increasing frequency as one would expect for lightning.

The main question in the interpretation of these data is whether the impulsive events were actually caused by lightning. At present, we have no other acceptable interpretation. The impulses were not caused by data transmission errors. Each data number is assigned a one-bit parity check in the instrument, and no errors were found. Also, the data were recorded on the spacecraft and transmitted to the ground twice with no disagreements between any of the data numbers, essentially eliminating the possibility of data transmission errors. For the three events in the lowest frequency channels, ~100 kHz, it is possible that the signals could have been produced by distortion or harmonics from impulsive electron plasma oscillations at about 45 kHz (see below). However, for the higher frequency events there is no possibility that the signals could have been caused by plasma waves. Of course, the signals could have been caused by some unusual type of spacecraft interference. However, because no comparable interference signals were found during the two control periods, this possibility seems unlikely. On the basis of these considerations, we conclude that lightning is the most likely source of the observed signals.

Because the range to the source is well known, the total radiated energy can be computed for each of the observed events. The radiated energy is about a factor of 2 to 4 times the peak energy of a typical midlatitude terrestrial lightning flash. It is of interest to compare these radiated energies with the Venera and Pioneer-Venus lightning measurements. Comparisons with Venera are complicated by the fact that for the Venera data the range to the source is unknown. If we take the typical peak electric field intensities given by Ksanfomality (*1*), $\sim 110\ \mu\text{V m}^{-1}\ \text{Hz}^{-1/2}$ at 10 kHz, and Ksanfomality's best estimate of the range R to the source, ~1200 to 1500 km, we can scale the intensities to the Galileo observations using $1/f^2$ and $1/R^2$ scaling laws. The scaled electric field intensity at Galileo works out to about $4 \times 10^{-15}\ \text{V}^2\ \text{m}^{-2}\ \text{Hz}^{-1}$ at 1 MHz. This intensity is about an order of magnitude greater than the observed intensities, a factor that could easily be accounted for by the uncertainty in the range to the source in the Venera data. Thus, the Galileo intensities appear to be in reasonable agreement with the Venera results.

Comparisons with the Pioneer-Venus data are much more difficult than those with Venera data. For the Pioneer-Venus data the intensities must be scaled over a much larger frequency range, into a region (~100 Hz) where the $1/f^2$ law is no longer valid. Worse yet, uncertainties in the propagation path of the whistler signals make it very difficult to relate the observed intensities to the energy radiated by the lightning flash. For these reasons, quantitative comparisons with the Pioneer-Venus data are beyond the scope of this report.

In addition to the lightning observations, a wide variety of plasma waves were also observed during the Venus flyby (Fig. 3). This spectrogram shows the electric and magnetic field intensities obtained from the medium- and low-frequency receivers, which provide low-rate measurements in 116 channels extending from 5 Hz to 160 kHz.

The 53-min data acquisition interval proved to be very well positioned relative to the bow shock. During this interval, four bow shock crossings were identified by the magnetic field (*6*) and plasma (*7*) investigators. The multiple shock crossings are caused by unsteady motions of the shock, which are commonly observed at other planetary bow shocks. The four shock crossings are shown by arrows at the top of Fig. 3, along with the corresponding plasma regions (solar wind and magnetosheath). A well-defined increase in both the electric and magnetic field noise levels can be seen in the magnetosheath, very similar to what is found in Earth's magnetosheath (*8*).

Throughout most of the region near and upstream of the shock, a very intense band of electric and magnetic field noise is present in the low-frequency channels, from about 5 to 50 Hz. This noise extends to about 0510 UT, where it abruptly terminates. This noise most likely consists of electromagnetic whistler mode waves or ion cyclotron waves. A preliminary comparison with the plasma data (*7*) does not reveal any obvious suprathermal particle distribution that could account for local generation of these waves, so the waves are probably propagating into the solar wind from a source near the shock.

At higher frequencies, from about 10 to 50 kHz, a weak band of electric field noise can be seen upstream of the shock. This noise consists of electron plasma oscillations (Langmuir waves) similar to those observed by Scarf *et al.* (*9*) in the Pioneer-Venus plasma wave data. At least two types of plasma oscillations can be seen, one consisting of a weak, nearly steady line at a frequency of about 45 kHz, which we identify as the electron plasma frequency, f_{pe} (see Fig. 3), and a second that is primarily shifted downward from the local electron plasma frequency. The downshifted component appears to be similar to the downshifted electron plasma oscillations observed upstream of the Earth's bow shock (*10*). These waves are almost certainly produced by suprathermal electrons streaming into the solar wind from the bow shock. The electron plasma oscillations abruptly stop at about 0512 UT. This termination probably represents a crossing of the electron foreshock boundary. The foreshock is a region of the solar wind that is magnetically connected to the bow shock. Beyond the foreshock, plasma oscillations cannot be excited because suprathermal electrons can no longer reach the spacecraft.

Near the end of the spectrogram, at about 0524 UT, a brief burst of electron plasma oscillations can be seen around 40 kHz. This burst probably represents a brief contact with the electron foreshock, most likely due to changes in the orientation of the solar wind magnetic field. By chance, a 78-s high-rate waveform frame was scheduled at almost exactly this time. These measurements give very high-rate samples of the electric field waveform at 201,600 samples per second, thereby providing high-resolution spectra of the waves that occurred in this region (Fig. 4). The plasma oscillations have a considerable amount of fine structure. A weak emission line can be seen at about 43 kHz. This frequency is probably the local electron plasma frequency. Large shifts, both upward and downward in frequency by as much as 20 kHz, are clearly evident. Also, the oscillations break up into intense, nearly monochromatic packets lasting only a fraction of a second. These highly structured emissions are strongly suggestive of soliton-like structures, which have been widely predicted by various theoretical studies (*11*).

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