

A rotation in the downstream field is also observed in the shock occurring at 04:17. At this time the PVO spacecraft was upstream of Galileo and in the solar wind. At Galileo, there were two rotations of the field just downstream of the fast mode compression of the field. There was a dip in field magnitude associated with each of the rotations, but the downstream field returned to its original upstream position after them. There was no clear signature of these rotations of the field in the upstream field as measured by PVO. As in shock E-1, there was a decrease in the magnitude of the field associated with the rotation. The component of the field in the shock surface rotated through roughly 720°, which is considerably different from the rotation at 03:42 UT in shock E-1.

These shock crossings may provide the first evidence that intermediate shocks can develop in a collisionless plasma. It is difficult to establish unambiguously that a compression closely associated with a change of the sign of the shock-plane component of the magnetic field is actually an intermediate shock. Elsewhere (21), we demonstrate that the measured field changes across the 03:43 shock crossings fall into the parameter regime required for an intermediate shock and that the 04:17 shock has a structure that we characterize as "exotic" and different from the expected form of either a fast or an intermediate shock. Because the field is variable, the analysis is not unambiguous but the results are highly suggestive of the rich and diverse shock physics we may find on further analysis of this remarkable data set. Further evidence concerning the nature of these two and other shocks will come from comparison with data from the plasma instrument on Galileo. It will be of particular interest to search for changes in density and temperature and to evaluate the anisotropy of the plasma pressure, which can modify the properties of the rotational discontinuity.

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1. For investigation of the interaction of the planet with the solar wind, we use a modified VSO (Venus-solar-orbital) coordinate system with  $X$  radially toward the sun,  $Z$  along the normal to Venus's orbit, and  $Y$  completing a right-hand triad. The modification corrects for the velocity of Venus's orbital motion, by rotating through 5° in a left-hand sense about the  $Z$  axis to obtain VSO- aberrated coordinates. In this system, the shock is, on average, symmetrical about the  $X$  axis. The trajectory was fortuitously aligned with the shock at downtail distances between -4 and -20  $R_V$  ( $1 R_V = 6052$  km = the mean radius of Venus).
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3. The data handling system is microprocessor-controlled, with a memory system that stores calibrated despun data for those periods during which the spacecraft is not acquiring full-time-resolution sci-

ence data. During the Venus flyby, this capability was used to fill (albeit at very low time resolution) the gaps between intervals for which the tape-recorded data were available.

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16. The multiplicity of solutions is naturally related to the three wave modes that can propagate in the magnetized plasma, that is, the fast and slow compressional waves and the shear intermediate wave. Just as a hydrodynamic shock in a neutral gas converts a supersonic flow to a subsonic flow, an MHD shock reduces a normal flow velocity initially above one of the phase velocities of the plasma

to a velocity below it.

17. Thus, the familiar fast shocks are (1,2) shocks as the normal flow velocity drops from superfast to subfast but superintermediate. Slow shocks are (3,4) shocks.
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## Lightning and Plasma Wave Observations from the Galileo Flyby of Venus

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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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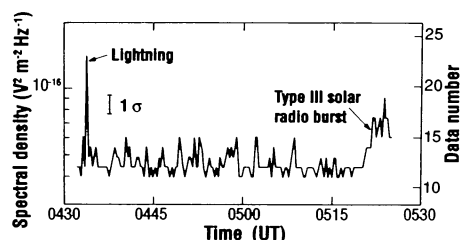
A. Roux and R. Gendrin, Centre National d'Etudes des Telecommunications/Centre de Recherches en Physique de l'Environnement, 38 Avenue du General Leclerc, 92131 Issy-les-Moulineaux-Cedex, France.

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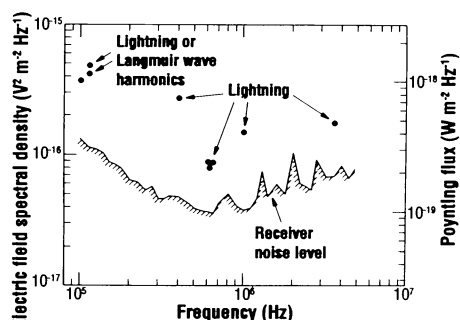
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instrument provides electric field measurements at frequencies up to 5.6 MHz. This frequency range is well above the frequency range of all previous radio and plasma wave measurements at Venus. At these high frequencies, it is possible to detect radio 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.



**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.

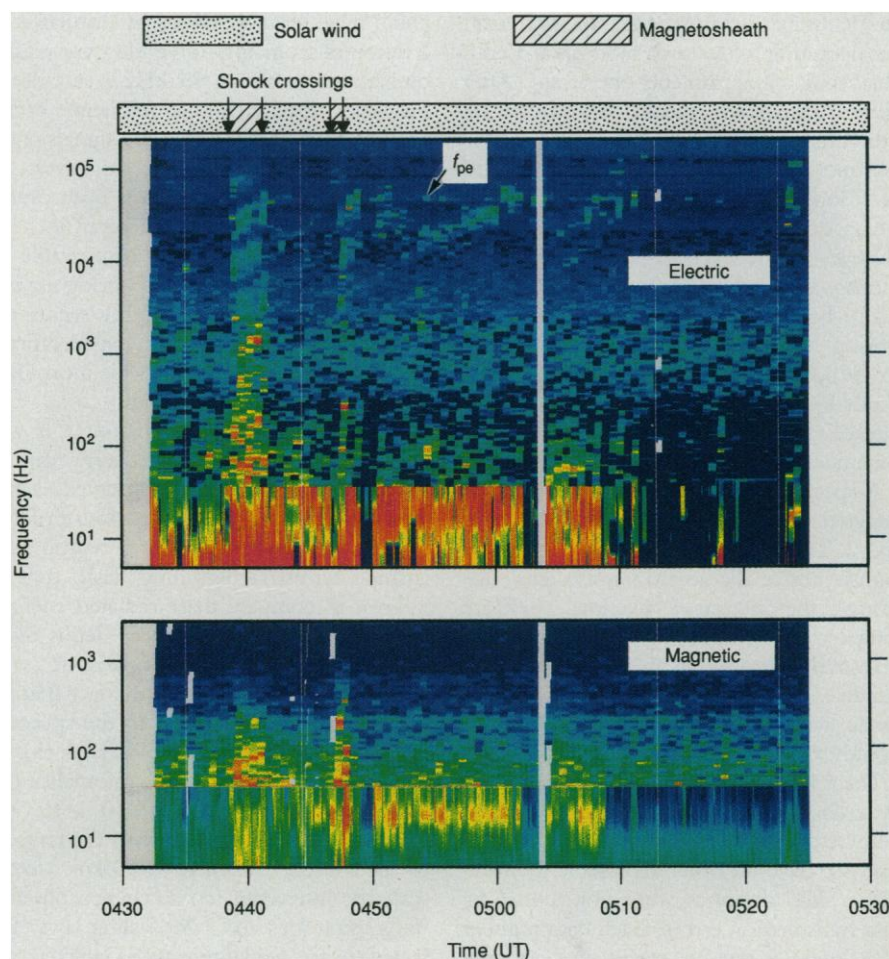
Because the integration time constant of the Galileo high-frequency receiver ( $\sim 70$  ms) was not ideally suited for detecting lightning, a study of mid-latitude terrestrial lightning was carried out with an engineering model to evaluate the sensitivity of the instrument to lightning. After correction for the typical radial distances ( $\sim 4$  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  $\sim 1$  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  $4.5 \times 10^{-17} \text{ V}^2 \text{ m}^2 \text{ Hz}^{-1}$  with fluctuations of about  $\pm 2$  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. 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.

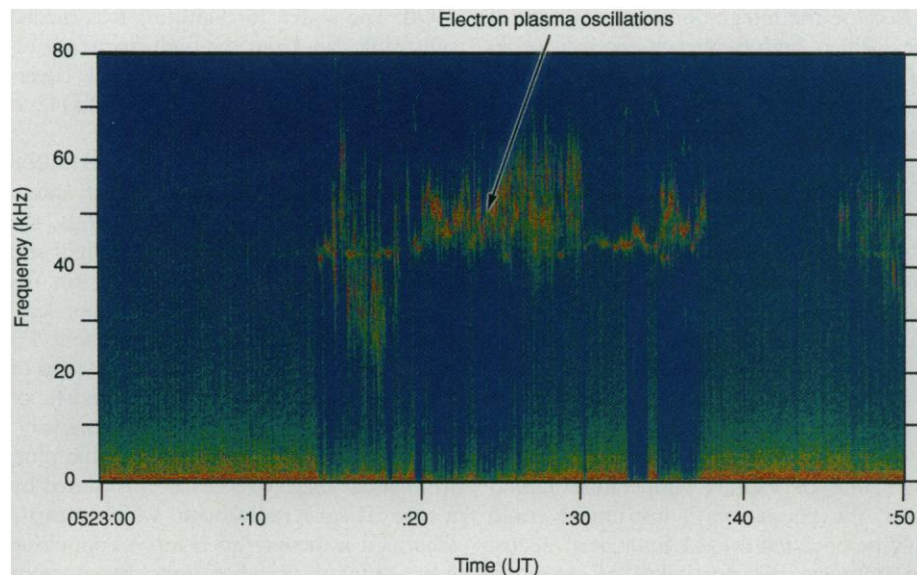


Fig. 4. A high-resolution frequency-time spectrogram of the electron plasma oscillations.

$N_{n-1}$ ,  $N_n$ , and  $N_{n+1}$  are successive data numbers in a given channel. Events were only counted if  $\delta$  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  $\delta$  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,  $\sim 100$  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 mid-latitude 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,  $\sim 1200$  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 ( $\sim 100$  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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## Energetic Particles at Venus: Galileo Results

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**At Venus the Energetic Particles Detector (EPD) on the Galileo spacecraft measured the differential energy spectra and angular distributions of ions  $\geq 22$  kiloelectron volts (keV) and electrons  $\geq 15$  keV in energy. The only time particles were observed by EPD was in a series of episodic events [ $\sim 0546$  to  $0638$  universal time (UT)] near closest approach (0559:03 UT). Angular distributions were highly anisotropic, ordered by the magnetic field, and showed ions arriving from the hemisphere containing Venus and its bow shock. The spectra showed a power law form with intensities observed into the 120- to 280-keV range. Comparisons with model bow shock calculations show that these energetic ions are associated with the venusian foreshock-bow shock region. Shock-drift acceleration in the venusian bow shock seems the most likely process responsible for the observed ions.**

A MAJOR EVENT IN THE MORE THAN 6-year journey of the Galileo spacecraft to Jupiter was its encounter with Venus on 10 February 1990. The encounter provided an opportunity to observe the Venus environment, and we report here results from the EPD on Galileo during the Venus flyby. These results represent the initial observations of energetic ions at Venus, because previous particle detectors flown by the planet did not cover the energy range over which we report ion measurements,  $\sim 22$  to 280 keV.

The EPD measures the fluxes, spectra, and angular distributions of ions  $\geq 20$  keV, electrons  $\geq 15$  keV, and elemental species (He through Fe)  $\geq 10$  keV per nucleon. The Low Energy Magnetospheric Measurement System (LEMMS) uses magnetic separation

and absorber foils to provide the ion and electron measurements. The Composition Measurement System (CMS) uses  $\Delta E \times E$  and time-of-flight techniques to provide the elemental species measurements. The two bidirectional detector heads, LEMMS and CMS, are mounted on a platform that can be rotated  $180^\circ$  by a stepper motor. This motion, coupled with the spacecraft spin, provides an angular coverage of a full  $4\pi$  Sr. A complete description of the EPD can be found in the report by Williams *et al.* (1).

Galileo operational constraints at Venus limited the use of the EPD to the following observational mode: (i) only the LEMMS detector head was activated, and (ii) angular distributions were obtained only in the plane perpendicular to the Galileo spin axis (which was pointed away from the sun). The resulting data were received at Earth when the tape recorder was played back on 19 November 1990, more than 9 months after the encounter.

The Galileo trajectory by Venus has been presented in the report by Johnson *et al.* (2). To place an appropriate perspective on the EPD observations, we show at the bottom of Fig. 1 the Galileo trajectory by Venus and a model bow shock for comparison. The EPD obtained angular scans in the plane perpendicular to the spacecraft spin axis,